



ZFITTER 1985 - 2013

– dedicated to *Pena Christova* on the occasion of her 70th birthday –

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We recapitulate the ZFITTER project.

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1. Introduction

To name a date of begin of the ZFITTER project is difficult. The first papers on electroweak loop calculations by D. Bardin and O. Fedorenko date back to 1976, but in another context. In September 1983 the Dubna-Zeuthen group started activity, due to the begin of the four-year long stay of S. Riemann and T. Riemann at JINR, Dubna. The name ZFITTER was invented in 1989 and replaced the former name ZBIZON for the software project. Finally, we chose the year 1985, when the article “Hunting the hidden standard Higgs” was published [1]. With this study, we began to take into account a finite, non-zero top quark mass m_t in the radiative corrections, in the context of e^+e^- -annihilation. To our knowledge, the paper contains the first plot confronting two LEP observables – weak mixing angle $\sin^2 \theta_W$ and Z boson mass M_Z – with their dependence on the

unknown top quark mass m_t and the also unknown Higgs boson mass M_H in the Standard Model [2–5]. We reproduce the plot here in figure 1.2, left. Both top quark and Higgs boson were not yet discovered at that time, and the actual experimental values for M_Z and $\sin^2 \theta_W$ had too huge errors to be included into the plot [6]: $M_Z = 92.9 \pm 16$ GeV and $\sin^2 \theta_W = 0.23 \pm 0.015$. The numbers in the figure are based on the one-loop Standard Model prediction for Δr , the weak correction to G_μ , deserving few lines of Fortran code. We remark as a curiosity that from 1985 to 2011, the article was quoted only once (by authors outside our group).

The LEP/SLC collaborations made exciting measurements of the Z boson resonance and of its mass, width, weak mixing angle etc., with an unexpected final accuracy:

$$M_Z = 91.1876 \pm 0.0021 \text{ GeV}, \quad (1.1)$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}, \quad (1.2)$$

$$\sin^2 \theta_{\text{weak}} = 0.22296 \pm 0.00028, \quad (1.3)$$

$$\sin^2 \theta_{\text{lept}}^{\text{eff}} = 0.23146 \pm 0.00012, \quad (1.4)$$

$$\sin^2 \theta_Z^{\text{MS}} = 0.23116 \pm 0.00012, \quad (1.5)$$

$$N_\nu = 2.989 \pm 0.007. \quad (1.6)$$

For the mass, this implies $\Delta M_Z/M_Z \approx 10^{-5}$. For the various definitions of the weak mixing angle see section 10 of [8]. And N_ν is the number of light neutrinos.

Figure 1.3 shows the rise of accuracy for M_Z due to LEP. Since the begin of the nineteen-nineties, a true scientific standard is the so-called blue-band plot of the **LEPEWWG**, based on ZFITTER [9–13] and another Standard Model package TOPAZ0 [14–16].¹ The March 2012



Figure 1.1: *ZFITTER* authors: Lida Kalinovskaya, Pena Christova, Dima Bardin, Tord Riemann, Sabine Riemann, Andrej Arbuzov. Photograph made on occasion of 5th Helmholtz International Summer School "Calculations for Modern and Future Colliders", July 23 - August 2, 2012, Dubna, Russia, CALC 2012. Right: Sasha Olshevsky, Arif Akhundov, Mark Jack. Fotos: © 2012 tordriemann@googlemail.com; JINR, Dubna; A. Akhundov (priv.); Physics at FAMU.

¹Reference [11] (1992) appeared as a CERN preprint because, at that time, we considered this to be more presti-

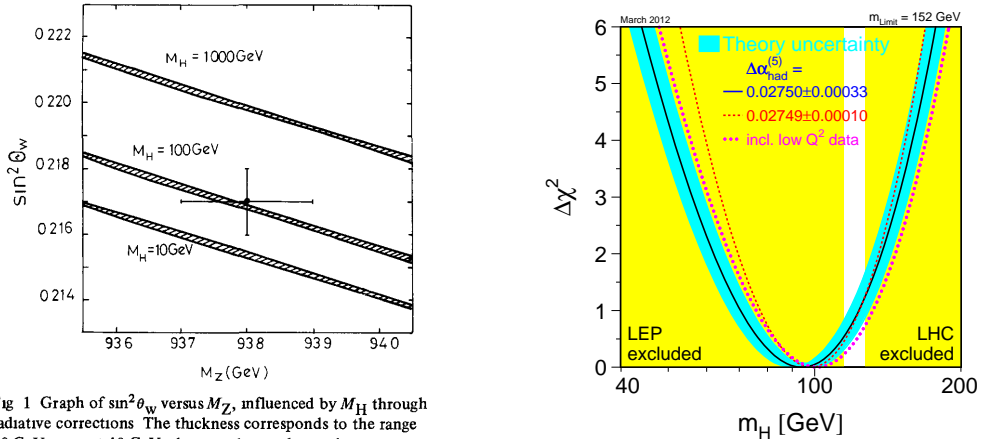


Fig 1 Graph of $\sin^2 \theta_W$ versus M_Z , influenced by M_H through radiative corrections. The thickness corresponds to the range $30 \text{ GeV} < m_t < 40 \text{ GeV}$, the error bars indicate the accuracy expected at Z boson factories.

Figure 1.2: Left: The first ever plotted LEP observables' dependence on the Higgs mass in the Standard Model (reprinted from *Physics Letters*, A. Akhundov, D. Bardin, and T. Riemann, "Hunting the hidden standard Higgs", volume B166, p. 111, Copyright (1986) [1], with permission from Elsevier.) Right: Blue-band plot of the LEPWWG [7] with a Standard Model Higgs boson mass prediction based on combined world data from precision electroweak measurements.

version is reproduced in figure 1.2, right. Both ZFITTER and TOPAZ0 are huge software packages with tens of thousands lines of Fortran code aiming at covering the complete known radiative corrections to the Z resonance peak in the reaction $e^+e^- \rightarrow \bar{f}f$. The top quark was predicted by M. Kobayashi and T. Maskawa in 1973 [17] and discovered in 1995 with a mass of about 173 GeV [18, 19]. Top quark mass data from precision electroweak measurements and from direct searches are collected in figure 1.3, right. After discovery of the top quark, the LEP data were no more competitive. The agreement of direct measurements (in 'all data') and indirect measurements (in 'all Z pole data') supports the validity of the Standard Model at the quantum loop level. Over the years the predictive power of the indirect searches for the Higgs boson mass improved considerably, and the discovery of the top quark was a crucial improvement for this. This is described in figure 1.4. In 2012, the LHC collaborations reported the discovery of a scalar particle with a mass of about 125 GeV [20, 21], which fits into these expectations from the indirect searches. It might well be that it is the particle predicted by Peter Higgs in 1964 [22, 23].

We live with the ZFITTER project for about 30 years now, and ZFITTER is yet in use for a diverse variety of applications, ranging from the global analyses of the LEPWWG to many graduation papers like e.g. [24]. Thirty years are a long term. It takes similarly long to prepare final results of big experiments at accelerators as LEP 1 (13 August 1989 - 1995), LEP 2 (1996 - 2 November 2000), HERA (1992-2007). The final analysis of the LEP 1 data for two-fermion production was published in 2005 [25] by the LEP collaborations and the LEPWWG, using ZFITTER v.6.42. The corresponding enterprise for LEP 2 data was finalized these days [26], using ZFITTER v.6.43.

The big laboratories invented scientific programs for a dedicated long-term preservation of

geous than e.g. a paper in the journal "Computer Physics Communications" devoted to publication of software. It was submitted to the internet archive hep-ph in 1994.

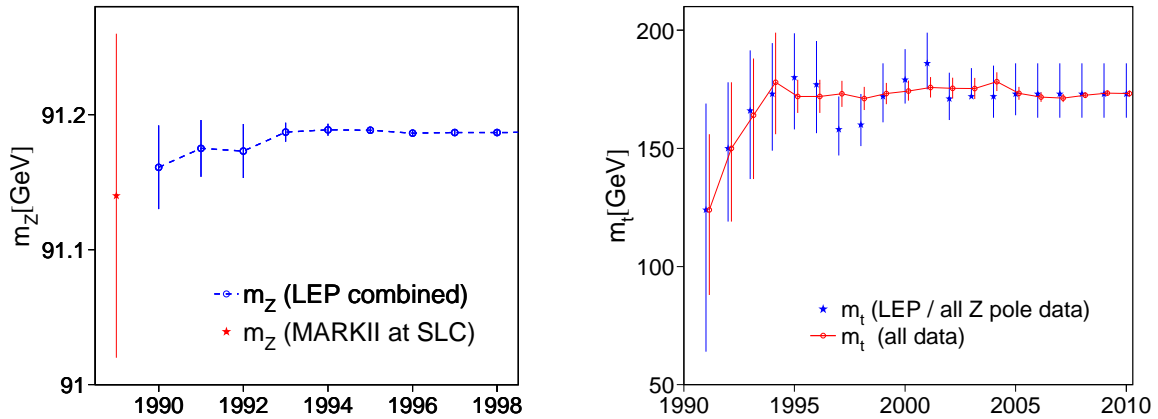


Figure 1.3: *Left: Z boson mass measurements at LEP. Earlier measurements are from UA1, UA2 at SPS (CERN) (see text, not shown in plot) and from MARKII at SLC (SLAC). Right: Top quark mass measurements.*

the experimental data, under the label “ICFA Study Group on Data Preservation and Long Term Analysis in High Energy Physics” [27]. One might assume that this is a self-evident issue of any physics collaboration. Physics is the science of reproducible observations in Nature and of their explanations/descriptions, and reproducibility deserves storage. But long-term storage is an unsolved problem, worth of any (reasonable) effort. DESY, as an example, founded in 2009 a “DESY Data Preservation Project”, mainly focusing on the HERA experiments H1, Hermes, ZEUS [28]. If such effort is justified for data, then it is also needed for the analysis tools, which were used for an extraction of the Model with its few parameters from the raw, or not-so-raw, Data. To our knowledge, the Big Labs do not plan to support long-term maintenance of software like ZFITTER. We, as authors, theoreticians and phenomenologists, have to mind by ourselves about maintenance of theory/phenomenology software.

Everybody knows that the very details of a data analysis cannot be described by few words. But for precision studies they are truly essential. Sometimes we say: “The description of the program is the program itself.” This is a helpful statement if “the program itself” is preserved over a long term in its state of use. ZFITTER did and does a lot to fulfil such a demand. See the webpage <http://zfitter.com>.

Preservation demands effort. There are 17 people involved in the DESY Data Preservation Project. At the other hand, if a theoretician says: I care about the availability of my old software, people start to smile. This aim does not give true credit points for a scientific carrier, in what phase of the carrier ever.

In fact, not only the so-called main author of ZFITTER, Dima Bardin, our “*primus inter pares*”, tends to lose interest in active support of ZFITTER over the decades. This applies to all of us, mainly because of our interest in studying or inventing something new. Nevertheless, we collected in 2005 some volunteers into a ZFITTER support group, which submitted in that year ZFITTER v.6.42 and in 2008 ZFITTER v.6.43 [12, 13]. ZFITTER v.6.44beta dates in 2013 [29].

Encouraged by the decreasing visibility of our ZFITTER support, in 2006 some experimentalists tried to re-program in C++ in a year's time the Standard Model library of ZFITTER from the published literature. Not just for fun, but in order to do better than ZFITTER: use a more modern programming language than Fortran, with more modularity than ZFITTER, a bit updated, with a GUI. In order to retain ZFITTER for a longer term. The project was proprietary until August 2012, and it faced two major problems. It proved to be impossible to do so without using the ZFITTER software itself to a large extent. Further, without cooperation with ZFITTER authors and the community of theoreticians, including extensive numerical cross-checks, such a project cannot succeed.²

Finally, there is much influence by institutes' directors and by the editors and publishers of physics journals on the engagement of scientists in the development of software. Not all of them seem to mind about proper acknowledgement and quotation of software. Some even say that software has no genuine scientific value by itself and advocate an absolutely free use of any software as common habit. If this *would become* common habit, nobody with inspiration and ambition would invest time to write complicated software for the use by other people, like the ZFITTER group - and other groups as well - does. We live in an academic world and we are valued by our scientific results, their originality, importance, curiosity, usefulness etc. Financing of our projects, of our working positions, our academic prestige depend on all that. We need proper quotation of our scientific results in case they are used. And we can only appeal and hope that the community understands this as a justified expectation, also for software.

As a key feature of user-friendly support, we stored for many years all the relevant versions of ZFITTER at a webpage for anonymous download. We collected about three dozen versions, covering more than 20 years. There are colleagues who take the freedom to use ZFITTER as if it were [open-source software](#) in the strictest meaning of the word. Despite the facts that academic research deserves strict, proper quotation, and that there are licence regulations (for ZFITTER this includes the [CPC licence](#)). In some countries there are even legal regulations.³

It is the aim of these notes to give an overview on the ZFITTER project. Maybe they can help to see theoretical software in particle physics as an intellectual enterprise like the other inventions of physics research - experimental set-ups, data, hypotheses, models, theories.

We would like to finish the introduction with two quotes.

Several times we all thought that the ZFITTER project is in its final phase of dying out. See for example the remark of Dima Bardin at the symposium “50 Years of Electroweak Physics: a symposium in honour of Professor Alberto Sirlin’s 70th Birthday”, in the year 2000 [30]:

“We would like to see the end of the ZFITTER project in the year 2000 and, therefore, a very natural question arises: What’s next?”

In the same year, members of the ZFITTER group were granted the prestigious “[JINR Award in Theoretical Physics](#)” of the Joint Institute for Nuclear Research, Dubna, Russia. For a document, see here: [certificate](#). The referee was Academician Prof. L. B. Okun from ITEP Moscow; he

²See subsection 6.2.

³Due to controversial positions, we closed the links for anonymous download from ZFITTER webpages in 2011; in 2012 the copies in the Andrew file system at CERN were removed.

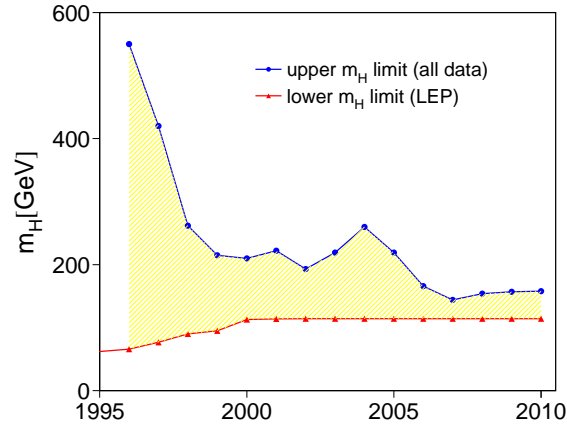


Figure 1.4: *Higgs boson mass measurements. The upper limits and the fit values for M_H derive from a combination of virtual corrections to LEP and similar data, top and W mass measurements, performed by the LEPWWG. The lower mass limit is due to LEP direct searches. The lower limits from data combinations are not shown.*

finished his estimate with the statement:⁴

“Overall, the project “ZFITTER Fortran program” represents a unique theoretical tool of world class. The project formed the basis of a close cooperation of experimentalists and theoreticians (with a series of workshops at CERN). With the accumulation of experimental data, the accuracy of the programs has been increased. The project has always found great interest at conferences. Its importance and the interest to it shows with numerous references in articles, reviews and monographies.

In the long term, with the advent of more precise experiments, ZFITTER will allow to take into account all two-loop electroweak corrections.

The series of theoretical articles on precision tests of the Standard Model at electron-positron colliders certainly deserves the award of the JINR prize 2000.

Academician L.B. Okun”

Our figures illustrate the development of mass predictions for Z boson (figure 1.3, left), top quark (figure 1.3, right), Higgs boson (figure 1.4). Here, ZFITTER has been useful until now. Okun’s proposition that ZFITTER will be used also in future is being fulfilled. We can only hope that our write-up might help to convince the present particle physics community that ZFITTER is worth some support by now and in future.

At the end of the introduction, we would like to reproduce the long(est) authors list of ZFITTER, see also <http://zfitter.com>:

A. Akhundov, A. Arbuzov, M. Awramik, D. Bardin, M. Bilenky, A. Chizhov, P. Christova, M. Czakon, O. Fedorenko (1951-1994), A. Freitas, M. Grünewald, M. Jack, L. Kalinovskaya, A. Olshcheyevsky, S. Riemann, T. Riemann, M. Sachwitz, A. Sazonov, Yu. Sedykh, I. Sheer, L. Vertogradov, H. Vogt. Few of us are seen in figure 1.1.

⁴The original document is in Russian, see [statement](#).

The list is not complete. According to the conventions of the software library of “Computer Physics Communications”, we should also include here all the co-authors who helped to prepare the program descriptions in 1989, 1999, 2005 [10, 12, 13].

2. ZFITTER in a nutshell, or: Is there a ZFITTER approach?

We never used the label “ZFITTER approach”. The reason is simple: There is no ZFITTER approach. If any, there is a kind of Dubna approach, or of Bardin’s group’s approach.

Nevertheless, other people use this phrase. Let us collect some distinguishing moments which might be the origin of some popularity of ZFITTER, but also of one or the other of our scientific projects:

- Unitary gauge.
We are working in the unitary gauge when studying the renormalization of the Standard Model. Most of the other groups use the ’t Hooft-Feynman gauge. But when looking at observable quantities, there is no difference left, due to the gauge invariance of perturbation theory. So, if everything is correct, there is no difference for the users.
- On-mass-shell renormalization scheme.
We are applying the on-mass-shell renormalization scheme, with few modifications. Other groups do the same for electroweak corrections.
- Analytical treatment of QED corrections.
ZFITTER is not a Monte-Carlo program. The Dubna group has an enormous experience in the analytical treatment of QED corrections, allowing us, sometimes, to come relatively close to the experimental set-ups by dedicated analytical integrations. Several different approaches may be chosen by users. The necessary computational time for fits to data is small compared to that of other projects.
- Realistic observables and pseudo-observables.
There is a plethora of observables, of quite different polarized and non-polarized cross-section combinations and asymmetries. Both so-called realistic observables (including real corrections) and pseudo-observables (after unfolding the realistic observables) may be used. With the different interfaces one may optimize a study appropriately.
- Form factors. Modularity.
We describe the effective Born cross-section in the Standard Model approach by (essentially) four (complex-valued) gauge invariant form factors per production channel.⁵ Plus a separated running QED coupling. This allows a modular programming, the efficient introduction of New Physics into the package, or the convenient export of the Standard Model corrections into another approach to the real corrections.
- Higher-order corrections.
Originally, we calculated the complete electroweak one-loop corrections to the Z resonance

⁵Massive top quark production deserves six form factors [31 – 33]. See also the in-depth discussion in [34].

physics. By time, there became more and more electroweak, QCD, and mixed higher-order corrections available, and we had to implement them into ZFITTER. In the nineteen-nineties these implementations dominated our efforts for ZFITTER. It is not the genuin theoretical work we like, but has to be done.

- Interfaces. Modularity.

ZFITTER is not a fitting program. But from the very beginning, we were aware of the fact that a data analysis at e.g. LEP may rest on different sets of assumptions, being incompatible to each other. The notion of interfaces was developed. The interfaces call the kernel of ZFITTER with different compositions of input variables, real corrections, an effective Born cross section. The users of ZFITTER can choose among few sample interfaces, or they write their own ones.

- Flags.

The use of ZFITTER may be controlled by flags to be set by users. Although this implies problems for the update by the authors, for users this is truly convenient.

- Descriptions.

ZFITTER is described for users at different levels of complexity. There are about 350 pages of instructions.

- Simplicity of file structure.

ZFITTER is easy to use. It has a simple file structure, is self-contained, and has a sample output. The installation at a computer is done and controlled within minutes. The installation of the user software, which is calling ZFITTER and performing data fits, writing tables and drawing figures, might be much more involved.

- Numerical cross-checks.

With very precise data available, as it was typical for LEP physics, a careful numerical control of the theory software became mandatory. Here, a lot of colleagues, including competitors of ZFITTER, invested huge collective efforts. Without that, one could not trust the impressive physical results of that era, or the long-term reliability of the code.

- Source-open programming.

The scientific seriosity of ZFITTER is trustable because its source code is publicly available. Because we expect that the usual academic conditions of use are respected, notably the CPC licence, we say it is source-open software. The meaning of the word open-source software is controversial and it should not be used for ZFITTER.

- Social aspects.

A software package of some complexity, written for use by other people, must be supported and, in case, updated. The authors need some contact with the users. And, last but not least, some licence regulations have to be fixed if the authors want to get their academic credit, e.g. in form of proper citations. Since the authors of ZFITTER are employed at some institutions distributed over several countries, it is of vital importance that these institutions interfere in a

constructive way. We are happy that this did happen for a very long period, in view of several social restructurings of institutions and even countries.

ZFITTER is a Fortran library of Standard Model predictions for the scattering process

$$e^+e^- \rightarrow \bar{f}f \ (+\gamma, \ +n\ \gamma) \quad (2.1)$$

at energies in the range $\sqrt{s} \approx 20$ GeV to 150 GeV, above quark bound states [meson factories] and below the top threshold. The package is to be called by interfaces

- in the Standard Model;
- in several model-independent approaches;
- with Z' bosons and similar physics extensions;
- etc.

One may evaluate

- realistic observables – polarized and non-polarized cross-sections and cross-section asymmetries with a variety of cuts on the final state
- (pseudo-)observables like M_Z , Γ_Z , $\sigma_{\text{had}}^{\text{tot}}$, R_{had} , $A_{\text{FB}}^{\text{lept}}$, λ_τ , $\sin^2 \theta_{\text{ew}}^{\text{eff}}$, ...
- the form factors, for use in another analysis program.

with different choices of input variables, e.g.

- M_Z , G_μ , m_t , M_H , α_{em} , α_s , ...
- M_Z , M_W , m_t , M_H , α_{em} , α_s , ...

3. Electroweak virtual corrections

The first weak one-loop calculations were published as Dubna preprints by D. Bardin and his PhD student O. Fedorenko in 1978 [35 – 37]. Together with P. Christova, then also PhD student of D. Bardin, the by now famous articles on the complete on-mass-shell renormalization of the electroweak Standard Model were published in Nuclear Physics B [38, 39], for fermion scattering. See also reference [40]. The corresponding studies for weak boson production and fermion-boson scattering are unpublished [41, 42].

These calculations were complete, but assumed all fermions to be massless. When experiments showed that at least the top quark should be heavy, the top mass dependence was included [1, 43, 44, 9]. Some studies of structural aspects in the renormalization of the Standard Model are [45, 46].

All this was done in the unitary gauge, while the other groups usually worked with the 't Hooft-Feynman gauge. Later, this difference was of some value because an agreement of two calculations performed in truly quite different gauges establishes a powerful cross-check of the numerics.

The first numerical program BFK (acronym for Bardin/Fedorenko/Khristova) was written in Fortran.

The Zeuthen partners, staying at Dubna from 1983 to 1987, worked out the renormalization of the electroweak Standard Model in the 't Hooft-Feynman gauge [47]. But because there was never a numerical program created, the results of this work were more or less useless; they had a mere educational aspect. Nevertheless, the experiences from that activity were used in order to perform the first calculation of flavor-changing Z boson decays into different lepton flavors.⁶ This was unpublished [48, 49]; see also [50]. An application to flavor-violating Z decays into different quark flavors was finally published [51]. Later, when we were working on precision predictions for LEP, the results could be easily transformed into the calculation of virtual top mass corrections in (flavor-diagonal) $b\bar{b}$ production at LEP and in Z decay [43]. And yet later, they were a starting point for studies of lepton number violation in e^+e^- annihilation with heavy neutrinos [52] and with supersymmetry [53].⁷

3.1 Sirlin's approach

The notion of form factors ρ and κ in the weak neutral current were, to our knowledge, introduced by A. Sirlin:⁸

- ρ – contains the electroweak corrections to the Fermi constant G_μ
- κ – contains the electroweak corrections to the weak mixing angle $\sin^2 \theta_W$

This approach allows to retain in the on-mass-shell renormalization scheme the Born definitions also in higher orders:

$$G_F^{\text{eff}} = \rho_Z G_\mu, \quad (3.1)$$

$$\sin^2 \theta_W^{\text{eff}} = \kappa_Z \sin^2 \theta_W, \quad (3.2)$$

where

$$\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8M_W^2}, \quad (3.3)$$

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}. \quad (3.4)$$

3.2 The HECTOR and ZFITTER approach

For general 4-fermion scattering amplitudes, one needs a more general description. This was first introduced, to our knowledge, by the Dubna/Zeuthen group, in 1988, in the article “Electroweak Radiative Corrections To Deep Inelastic Scattering At HERA. Neutral Current Scattering” by D. Bardin, C. Burdik (Dubna), P. Khristova (Shoumen), T. Riemann (Zeuthen) [55]. The corresponding software is retained until today as the Fortran package HECTOR [56]. So, strictly speaking, one might call this the HECTOR approach.

⁶We mention for curiosity that the numerics of this one-loop project was performed with a pocket calculator TI-57 with 50 program steps. The program had to be typed in after switching on. The price of the device was 120 DM in the CERN shop.

⁷Several of the results in supersymmetry found in the literature turned out to be just wrong when we had a look at them.

⁸For a historical perspective, see reference [54].

We use four complex form factors $\rho, \kappa_{\text{ini}}, \kappa_{\text{fin}}, \kappa_{\text{ini-fin}}$ for the parameterization of the weak amplitude, including the WW and ZZ box diagrams. In the article “A Realistic Approach to the Standard Z Peak” by D. Bardin, M. Bilenky, G. Mitselmakher (Dubna), T. Riemann, M. Sachwitz (Zeuthen) [9], we excluded the weak WW and ZZ box diagrams from the form factors, making them independent of the scattering angle. This is of advantage at LEP where these box diagrams have minor numerical influence. When form factors are independent of the scattering angle, analytical phase space integrations become possible. In ZFITTER, there is an option to switch between the approaches.

The Born amplitude is factorized into two pieces with vector coupling v_i and axial vector coupling a_i of a fermion i to the Z-boson:

$$A \otimes B \equiv [\bar{u}_i \gamma_\mu (v_i + a_i \gamma_5) u_i] \times [\bar{u}_f \gamma^\mu (v_f + a_f \gamma_5) u_f], \quad (3.5)$$

and is generalized by loop corrections to

$$A_{vv} \gamma \otimes \gamma + A_{av} \gamma \gamma_5 \otimes \gamma + A_{va} \gamma \otimes \gamma \gamma_5 + A_{aa} \gamma \gamma_5 \otimes \gamma \gamma_5, \quad (3.6)$$

or, equivalently,

$$B_{LL} \gamma(1 + \gamma_5) \otimes \gamma(1 + \gamma_5) + B_{\gamma L} \gamma \otimes \gamma(1 + \gamma_5) + B_{L\gamma} \gamma(1 + \gamma_5) \otimes \gamma + B_{\gamma\gamma} \gamma \otimes \gamma. \quad (3.7)$$

With Z boson and photon exchanges:

$$\mathcal{M} = \mathcal{M}_\gamma + \mathcal{M}_Z, \quad (3.8)$$

$$\mathcal{M}_\gamma \sim F_A [\gamma \otimes \gamma], \quad (3.9)$$

$$\mathcal{M}_Z \sim G_\mu \rho_Z [\gamma \gamma_5 \otimes \gamma \gamma_5 + v_q \gamma \otimes \gamma \gamma_5 + v_l \gamma \gamma_5 \otimes \gamma + v_{ql} \gamma \otimes \gamma]. \quad (3.10)$$

In Born approximation, it is

$$v_{ql} \approx v_q \times v_l. \quad (3.11)$$

The form factors $F_A, \rho, \kappa_q, \kappa_l, \kappa_{ql}$ are complex-valued functions of s and t :

$$F_A(s) = \frac{\alpha_{QED}(s)}{\alpha_{em}} = 1 + \delta\alpha_{QED}(s), \quad (3.12)$$

$$\alpha_{em} = \frac{1}{137 \dots}, \quad (3.13)$$

$$a_f \equiv 1, \quad f = q, l \quad (3.14)$$

$$v_f(s, t)^{\text{eff}} = 1 - 4 \sin^2 \theta_W |Q_f| \kappa_f(s', t), \quad f = q, l \quad (3.15)$$

$$v_{ql}(s, t)^{\text{eff}} = v_q + v_l - 1 + 16 \sin^4 \theta_W |Q_q Q_l| \kappa_{ql}(s', t), \quad (3.16)$$

where we use $Q_e = -1$. From [57], eq. (3.3.1), we quote:

$$\begin{aligned} \mathcal{A}_Z^{\text{OLA}}(s, t) = & i e^2 4 I_e^{(3)} I_f^{(3)} \frac{\chi_Z(s)}{s} \rho_{ef}(s, t) \left\{ \gamma_\mu (1 + \gamma_5) \otimes \gamma_\mu (1 + \gamma_5) \right. \\ & \left. - 4 |Q_e| s_W^2 \kappa_e(s, t) \gamma_\mu \otimes \gamma_\mu (1 + \gamma_5) - 4 |Q_f| s_W^2 \kappa_f(s, t) \gamma_\mu (1 + \gamma_5) \otimes \gamma_\mu \right\} \end{aligned} \quad (3.17)$$

$$+16|Q_e Q_f|s_w^4 \kappa_{e,f}(s,t) \gamma_\mu \otimes \gamma_\mu \Big\}.$$

The form factors may be used, in analogy to the Z decay matrix element of Sirlin, for definitions of effective vector and axial vector couplings and of an effective weak mixing angle:

$$G_\mu^{\text{eff}} = \rho_{ef} G_\mu, \quad (3.18)$$

$$\sin^2 \theta_{W,e}^{\text{eff}} = \kappa_e \sin^2 \theta_W, \quad (3.19)$$

$$\sin^2 \theta_{W,f}^{\text{eff}} = \kappa_f \sin^2 \theta_W, \quad (3.20)$$

$$\sin^2 \theta_{W,ef}^{\text{eff}} = \sqrt{\kappa_{ef}} \sin^2 \theta_W. \quad (3.21)$$

The unique definition of an effective weak mixing angle is lost.

The first applications of the calculations of weak corrections by the Dubna group were applied, together with N. Shumeiko, to deep-inelastic scattering; see e.g. [58, 59]. There were close relations to the NA-4 experiment at CERN with JINR participation. The form factors ρ and κ are simply related to the one-loop form factors introduced in the original renormalization articles by Bardin and Fedorenko (1978) [35–37] and Bardin, Christova, Fedorenko (1980) [38, 39]:

$$\rho_{ef} = 1 + F_{LL}(s,t) - s_w^2 \Delta r, \quad (3.22)$$

$$\kappa_e = 1 + F_{QL}(s,t) - F_{LL}(s,t), \quad (3.23)$$

$$\kappa_f = 1 + F_{LQ}(s,t) - F_{LL}(s,t), \quad (3.24)$$

$$\kappa_{ef} = 1 + F_{QQ}(s,t) - F_{LL}(s,t). \quad (3.25)$$

The corresponding relations of form factors F_{ij} and the Z boson matrix element are:

$$\begin{aligned} \mathcal{M}_Z^{\text{OLA}} = & i \frac{g^2}{16\pi^2} e^2 4 I_e^{(3)} I_f^{(3)} \frac{\chi_Z(s)}{s} \\ & \times \left\{ \gamma_\mu (1 + \gamma_5) \otimes \gamma_\mu (1 + \gamma_5) F_{LL}(s,t) - 4|Q_e|s_w^2 \gamma_\mu \otimes \gamma_\mu (1 + \gamma_5) F_{QL}(s,t) \right. \\ & \left. - 4|Q_f|s_w^2 \gamma_\mu (1 + \gamma_5) \otimes \gamma_\mu F_{LQ}(s,t) + 16|Q_e Q_f|s_w^4 \gamma_\mu \otimes \gamma_\mu F_{QQ}(s,t) \right\}. \end{aligned} \quad (3.26)$$

So far we discussed matrix elements. The differential cross section for $e^+e^- \rightarrow f\bar{f}$ is:

$$\begin{aligned} \frac{d\sigma}{d\cos\vartheta} = & \frac{\pi\alpha_{em}^2}{2s} \left\{ (1 + \cos^2\vartheta) [K_T(\gamma) + \Re e(\chi(s) K_T(I)) + |\chi(s)|^2 K_T(Z)] \right. \\ & \left. + 2\cos\vartheta [K_{FB}(\gamma) + \Re e(\chi(s) K_{FB}(I)) + |\chi(s)|^2 K_{FB}(Z)] \right\}, \end{aligned} \quad (3.27)$$

with

$$\chi(s) = \frac{G_F}{\sqrt{2}} \frac{M_Z^2}{8\pi\alpha} \frac{s}{s - M_Z^2 + i\Gamma_Z M_Z}. \quad (3.28)$$

One has to care about the choice of a constant Z boson width γ_Z or an s -dependent width Γ_Z here [60].

The effective couplings are:

$$K_T(\gamma) = c_{color} Q_i^2 Q_f^2 |F_\gamma(s)|^2 \quad (3.29)$$

$$=_{Born} c_{color} Q_i^2 Q_f^2,$$

$$K_T(I) = 2c_{color} |Q_i Q_f| F_\gamma(s)^* \rho_{if}(s, t) v_i v_f \quad (3.30)$$

$$=_{Born} 2c_{color} |Q_i Q_f| v_{B,i} v_{B,f},$$

$$K_T(Z) = c_{color} |\rho_{if}(s, t)|^2 (1 + |v_i|^2 + |v_f|^2 + |v_{if}|^2) \quad (3.31)$$

$$=_{Born} c_{color} (v_{B,i}^2 + a_{B,i}^2)(v_{B,f}^2 + a_{B,f}^2),$$

$$K_{FB}(\gamma) = 0, \quad (3.32)$$

$$K_{FB}(I) = 2c_{color} |Q_i Q_f| F_\gamma(s)^* \rho_{if}(s, t) \quad (3.33)$$

$$=_{Born} 2c_{color} |Q_i Q_f| a_{B,i} a_{B,f},$$

$$K_{FB}(Z) = 2c_{color} |\rho_{if}(s, t)|^2 2\Re(v_i v_f + v_{if}) \quad (3.34)$$

$$=_{Born} 2c_{color} (2v_{B,i} a_{B,i})(2v_{B,f} a_{B,f}).$$

Here, i denotes the initial state and f the final state. For the Drell-Yan process $\bar{q}q \rightarrow l^+ l^-$, it is $q = u, d$ and $f = l$.

The c_{color} is the color factor, e.g. $c_{color} = 3$ for initial state quarks and final state leptons.

A similar formula describes the special case of Bhabha scattering [61, 12, 62, 63]. The 1990 article, a numerical comparison with W. Hollik [62], seems to be the most precise prediction for the effective Born cross-section of Bhabha scattering until today.

At the end of the subsection, we would like to emphasize that notions of form factors are not unique. We split, for purely phenomenological reasons, the matrix element into two pieces: a photon amplitude and a Z boson amplitude. The calculation of the running QED coupling is technically quite different from that of the weak loop diagrams. So this is reasonable. Gauge invariance justifies it, but only if handled with care. There are diagrams which mix a photon and a Z boson amplitude, and this is gauge dependent. So, in ZFITTER we decided to include all the corrections but the fermionic self-energy insertions, a bit arbitrary, into the Z boson amplitude.

Such a separation of photonic and weak terms is wishful also for the charged current W boson mediated amplitude. But a gauge-invariant separation of (virtual and real) photonic corrections from W boson exchange is impossible. In HECTOR [64, 56], we found a way to do well-defined separations by considering logarithmic terms and just explicitly defining some rule. This really worked out. Years later, when building a software for $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$, we could take over the weak charged current form factor into the Monte Carlo program of S. Jadach and Z. Was [65]. This reaction is, for $\nu = \nu_e$, unique: It depends both on neutral current and charged current amplitudes.⁹

Similar problems have been discussed when the ZFITTER form factors were adapted to atomic violation measurements [66].

3.3 Drell-Yan processes

We went a bit into the details of a correct ansatz for the effective Born approximation in the Standard model in $e^+ e^-$ -annihilation. The situation in a Drell-Yan process is quite similar. One

⁹Bhabha scattering has also s- and t-channel exchanges, but only of neutral current type.

may study e.g. the running of the weak mixing angle $\sin^2 \theta_W^{\text{eff}}(s')$ as a function of the scale s' from a hard cross-section $\sigma_0(s')$:

$$\sigma_0(s') = \mathcal{L}_u \sigma_0(u\bar{u} \rightarrow l^+ l^-) + \mathcal{L}_d \sigma_0(d\bar{d} \rightarrow l^+ l^-), \quad (3.35)$$

where both hard scattering cross-sections $\sigma_0(u\bar{u} \rightarrow l^+ l^-)$ and $\sigma_0(d\bar{d} \rightarrow l^+ l^-)$ depend on four complex valued, process-dependent form factors $\rho_{ql}, \kappa_q, \kappa_l, \kappa_{ql}$ with $q = u, d$. The σ_0 depends on s' , but also on the scattering angle θ . Further, we have not only initial and final state photonic corrections, but also initial-final state interferences.

An elegant way to cover at least part of the complexity of all this in a modern QCD Monte Carlo program is the following:

- Define a photon exchange amplitude.
- Define a Z exchange amplitude.
- Split the v_{ql} into a Z-part and a photon part:

$$v_{ql} \rightarrow (v_{ql} - v_q v_l) + v_q v_l. \quad (3.36)$$

– Assume a Born like structure with form factors ρ, v_q, v_l and put the deviation from that structure, which is contained in the difference $(v_{ql} - v_q v_l)$, into the photon amplitude.

In an unpublished paper of 1991 [67], A. Leike and T. Riemann worked out the influence of Z' -physics on the evaluation of weak form factors. The idea of reshuffling matrix elements in form factors was invented there and is now independently re-used as clever inclusion of ZFITTER's weak form factors into a Monte Carlo code, which was originally made for the description of QCD corrections to Drell-Yan processes.¹⁰

Evidently, once there are accurate data, one has to carefully understand how to model the correct physics ansatz with a smaller number of parameters. This is under study by experimentalists presently.

4. Real corrections, mostly due to QED

Around 1983 we began to envisage some contribution to the description of the Z boson resonance as it was planned to be studied at LEP. There existed several articles on electroweak radiative corrections. Let us mention the electroweak study by Wetzel in 1982 [68] and that by Lynn and Stuart in 1984 [69], or the MC program MUSTRAAL by Berends, Kleiss, Jadach in 1982 [70]. It was not evident to us that we might contribute some novel results, and we decided therefore to study real photon emission first.

The Dubna group has an enormous experience in the analytical treatment of QED corrections, first mostly applied to t -channel exchange processes. We should mention here the close contacts with Dubna experimentalists of the NA-4 collaboration at CERN. The subtraction method for the treatment of infra-red singularities was worked out in 1976 in a seminal paper [71]. The divergent part of the cross-section is, in simplified form, integrated over the whole phase space, and at the same time subtracted from the exact squared matrix element. The difference can be integrated

¹⁰W. Sakumoto, private information.

numerically, and the isolated term is sufficiently simple for an analytical treatment. In practice, this can become quite involved, see reference [72].

The first articles treated just photonic corrections, taking into account mass effects. The very first one was on pure QED corrections in e^+e^- annihilation, by A. Akhundov (Baku), D. Bardin (Dubna), O. Fedorenko (Petrozavodsk), T. Riemann (Dubna): “Some Integrals For Exact Calculation Of QED Bremsstrahlung”, an unpublished JINR Dubna preprint [73], followed by [74, 75]. Then we extended the integrational technology to experimental set-ups with Z boson resonance phenomena, including mixing phenomena of Z boson and photon. This sounds easy, but there were several conceptual problems to be solved. As a result, ZFITTER relies now on several versions of semi-analytical formulae with low-dimensional numerical phase space integrations left. At the time of LEP experiments, this was extremely useful. For an unfolding of measured cross-sections into pseudo-observables, or for multi-dimensional fits, the computing time of an analysis code was absolutely decisive. The inclusion of certain kinematical cuts was a wish expressed by experimentalists. Computers were not so advanced. There were no personal computers, and workstations were also not yet on the market. In Dubna, there were one or two terminal stations for theoreticians, and we had to queue up every day. In Russian Winter, the terminal room (with one terminal) was a bit cold at temperatures close to zero centigrades, because the windows did not close exactly. The upper left corner of the terminal screen was blind. Often the terminal in the theory building was blocked by Riemann, Bardin, Akhundov from 9 to 12 in the morning. Not everybody was amused.

In case of quark-pair production, or Z or W boson decays into quarks, the final state will get QCD modifications. The corrections are contained in so-called radiator functions. Their implementation in ZFITTER relies on calculations by a variety of colleagues and is described in the various ZFITTER descriptions, notably in references [9, 11 – 13]. Useful representations are also e.g. [76 – 79].

The treatment of the complete set of QED corrections related to real emission of photons in ZFITTER is quite specific. The higher-order corrections have been typically taken over from the literature, as it is documented, notably in references [12, 13]. An important example is reference [80]. The main work had to be performed at one-loop order, plus soft photon exponentiation. It was clear that the numerical effects will be important for the experimental analyses. There were several Monte-Carlo programs available, e.g. [81, 70, 82 – 85] and the references therein. See also the report [86]. We aimed at an alternative, analytical integration of the three-dimensional photon phase space integrals. The necessary techniques have been developed step by step over a longer period, and originate to a large extent from studies for deep-inelastic scattering, e.g. $lN \rightarrow lX$ [72]. In the presence of the Z boson resonance in the s-channel, one is faced with the additional need to perform a correct treatment of the Breit-Wigner propagator, a truly complex function. Further, there is a mixing of photon and Z boson exchange. This γZ mixing was studied e.g. in [47, 51, 87, 88]; this issue was settled by a formal Dyson summation of the γ, Z propagator matrix. The Z boson propagator with the finite width may become an issue for analytical integrations. In squared matrix elements, we are faced with $\gamma\gamma$, γZ and ZZ interferences. The latter are dominating around the Z boson pole, and they will contain squared Z boson propagators. To perform analytical phase space integrations with such a term inside looks difficult. An important, simple idea is to perform

a partial fraction decomposition in order to linearize the integrand:

$$\begin{aligned} \left| \frac{1}{s - M_Z^2 + iM_Z\Gamma_Z} \right|^2 &= \frac{1}{2iM_Z\Gamma_Z} \left(\frac{1}{s - M_Z^2 + iM_Z\Gamma_Z} - \frac{1}{s - M_Z^2 - iM_Z\Gamma_Z} \right) \\ &= -\frac{1}{M_Z\Gamma_Z} \Re \left(\frac{1}{s - M_Z^2 + iM_Z\Gamma_Z} \right). \end{aligned} \quad (4.1)$$

At first glance this looks bizarre because the complete answer seems to carry an overall factor $s/(M_Z\Gamma_Z)$. Evidently, one may use complex integration theory, so this is good. The overall pre-factor gets divergent for vanishing Z width, but this is the technical expression of the well-known radiative tail, so this is also good.

We tried the approach, and calculated the complete one-loop QED corrections for the total cross-section and the forward-backward asymmetry around the Z resonance without a cut. The results for initial state radiation, final state radiation and the initial final state interferences were rather compact and looked explicitly reasonably behaving.¹¹ The results were published as preprint in [90] and refined a bit in [91]. The paper could not be published in Nuclear Physics B because the referee found it not close enough to the experimental set-up. Nevertheless, it is a nice piece of work and served for many years as an important numerical etalon for precision comparisons.

As a by-product, we understood that one may calculate the photonic corrections to the initial-final state interference of the γZ interference as the arithmetical means of the corrections to the ZZ and $\gamma\gamma$ initial-final state interferences:

$$R_{ini-fin}(Z, Z_2) = \frac{1}{2} [R_{ini-fin}(Z, Z) + R_{ini-fin}(Z_2, Z_2)], \quad Z_2 = \gamma. \quad (4.2)$$

Here, Z_2 is a second vector boson. For a proof see reference [87]. This is not of utmost importance here. When we later studied QED corrections for Z, Z' production with a heavy Z' boson, then we had the newly appearing initial-final state part of the ZZ' interference at the disposal without a new calculation [92–96].

Later we refined the techniques, and finally ZFITTER enables the calculation of

- exact, completely integrated one-loop photonic corrections without cuts [91];
- convolution integrals for cross-sections with soft photon exponentiation [97];
- the corresponding angular distributions [98];
- convolution integrals with integrated angular cuts [99];
- convolution integrals with integrated acceptance cuts, combined further with an acollinearity cut [100].

¹¹In fact, it took us nearly half a year of heavy fighting with SCHOONSCHIP, because we did not agree, at the Z boson peak, with the numerics of the Monte-Carlo program MUSTRAAL [70, 89]. The MUSTRAAL was available via CPC, and we could run it at Dubna. The mistake was, as often, trivial, but influential. The final 5 digits agreement convinced us that our Breit-Wigner treatment makes sense and is operational.

The sophisticated final state phase space treatment with cut on the acollinearity final state fermions goes back to G. Passarino (1982) [101] and is relatively close to realistic experimental cuts for lepton final states. The complete analytical QED corrections were worked out for this case by M. Bilenky and A. Sazonov [100] and became part of ZFITTER. The truly nice paper remained unpublished, unfortunately. Later, we recalculated these corrections for ZFITTER from the scratch (unpublished, see references [102 – 105]). We performed two minor corrections and got very nice, compact formulae for the special case of no cut for the fermion production angle [106].

Finally, all this was sufficiently close to what the experimentalists could derive from their Monte-Carlo simulations for a confrontation with theory.

We wrote relatively monstrous programs in Veltman's SCHOONSCHIP [107, 108] to be run at a CDC-6500 main frame at JINR Dubna. Bardin and Fedorenko where, in parallel with Vladimirov and Tarasov, among the first using SCHOONSCHIP at JINR in 1976.¹² Colleagues from Moscow came to JINR regularly in order to use the CDC-6500 main frame because comparable computers were subject of the US embargo policy and thus not available for civil use in Soviet Union at that time. JINR, Dubna, as an international research center, was privileged in that respect.¹³ A comprehensive review on the use of computer algebra at JINR is [109]. Later FORM [110, 111] was invented by Jos Vermaseren and we could run it at personal computers. The first article typeset in latex was presumably [98], and the first article submitted to the hep-ph archive dates in 1994; The archive hep-ph was opened in 1992.

At a certain moment we realized that analytical integrations are fine; but if the sensitivity to the Z boson width becomes sufficiently large, then it will matter whether the width is a pure constant γ_Z as in a normal Breit-Wigner function, or whether it arises from a quantum field theoretical calculation and will thus depend on the kinematics, $\Gamma_Z(s)$. In the latter case, it is (roughly speaking) the imaginary part of the Z boson self-energy function, which is by itself s -dependent; and for initial state corrections s' -dependent. The s' is one of the integration variables. We remembered that the s -dependence is, to a very high accuracy, just $M_Z \Gamma_Z(s) = (s/M_Z) \Gamma_Z$, and this observation enables us to change the propagators into functions with a constant width, allowing not only a good estimate of the different approaches, but also furtheron the analytical integrations: The differences of mass and width in the two approaches derives from the following identity [60]:¹⁴

$$\frac{1}{s - M_Z^2 + iM_Z\Gamma_Z(s)} \equiv c \frac{1}{s - m_Z^2 + im_Z\gamma_Z}, \quad (4.3)$$

with

$$m_Z = M_Z - \frac{\Gamma_Z^2}{2M_Z} = M_Z - 34 \text{ GeV}, \quad (4.4)$$

$$\gamma_Z = \Gamma_Z - \frac{\Gamma_Z^3}{2M_Z^2} = \Gamma_Z - 0.934 \text{ MeV} \approx -1 \text{ MeV}. \quad (4.5)$$

¹²A. Akhundov, D. Bardin, L. Bobyleva, V. Gerdt, I. Shidkova, W. Lassner, V. Rostovzev, O. Tarasov, R. Fedorova and D. Schirkov received in 1986 the JINR Award in Theoretical Physics for "Introduction, development and use of computer systems for analytical calculations at central computers of the central computing installations of JINR". We are grateful to V. Gerdt for a clarifying email exchange.

¹³We are grateful to Andrei Kataev reminding about this fact.

¹⁴The Z boson mass shift was discovered by a numerical study of the Z boson peak in parallel in [112].

Here, $M_Z = 91187.6$ GeV and $\Gamma_Z = 2.4952$ GeV have to be chosen as the usual PDG values. Later we worked out an approach to a model-independent Z boson peak analysis inspired by S-matrix theory, relying naturally on m_Z, γ_Z . Not only for the Z boson peak cross-section, but also for asymmetries. The point here again is a proper treatment of QED corrections [113 – 118].¹⁵

In fact, the idea to use m_Z, γ_Z instead of M_Z, Γ_Z was born while listening to a talk on string theory at a conference, while reading a paper on QED corrections with complicated phase space cuts by Passarino [101].

The Z boson parameter relations (4.4) and (4.5) become essential when two-loop electroweak corrections are determined in ZFITTER. This is carefully described in [119], where the complete electroweak two-loop corrections to the leptonic weak mixing angle have been calculated. See also section 6. It is remarkable that the shift of the Z boson width due to the change of scheme (s-dependent or constant Z boson width) amounts to 1 MeV and is larger than the corresponding shift from the genuine weak NNLO corrections. Compared to the experimental error of 2.3 MeV, the shift is small. The authors of [119] did not take the correction into account because it is formally beyond the NNLO order and thus among the systematically neglected terms.¹⁶ One should consider the term as an indication of the size of unknown higher order terms.

What we describe here is about the state of real emission affairs in ZFITTER at the end of the nineteen-eighties. Final state mass effect treatments were refined in [120 – 122]. Some additional QED corrections, due to light fermion pair emission and higher order photonic effects, needed for a proper treatment at LEP 2 energies were later added [123, 124]. See also reference [125].

Careful studies of ZFITTER physics updates originated in these years [126, 126, 78, 127].

5. Competition and cooperation

5.1 1989 - First LEP publications

In 1989, the world changed quite a bit. Participation at the Ringberg Workshop on LEP physics in Germany became possible [128]. The NATO supported RADCOR conference on radiative corrections and their applications to experiments in Brighton, the first one of a series, was open to Eastern Country physicists [129, 130]. We remember the stimulating atmosphere of the 1989 LEP physics workshop at CERN [129, 131]. And LEP became operative in August 1989. The first months were exciting. A good knowledge of radiative corrections was needed from the very beginning, just in order to discriminate between trivial radiative effects and New Physics. Several unpublished ZFITTER related theory studies appeared in this period, e.g. [132 – 135]. In [135], approximate parameterizations of $O(\alpha\alpha_s)$ corrections [136] were derived in order to speed-up the numerics. The Fortran routines of B. Kniehl [137] improved this later furtheron. The LEP collaborations performed the first Z line shape analyses. We were closely related to the L3 collaboration [138 – 145] and to DELPHI [146 – 150]. A review of the latter is [151].

Among the first DELPHI papers was [146]. From the ZFITTER group, D. Bardin and G. Mitselmaker were DELPHI authors. The paper quotes for the theory on the Z line shape G. Burgers [152] and A. Borrelli et al. [153]. In [149], the Z line shape analysis used the software packages

¹⁵The corresponding software package SMATASY is supported by Martin Grünewald.

¹⁶Ayres Freitas, private information.

ZAPPH and ZHADRO by G. Burgers [152]. In [148], March 1990, our papers [9, 100] are quoted. And in [150] the package ZFITTER/ZBIZON with reference to the internal note DELPHI 89-71 PHYS 52 and to [9, 10] was used.¹⁷

A similar approach was observed in the L3 collaboration, where ZFITTER authors T. Riemann, M. Sachwitz and H. Vogt were collaborating in 1989. The internal note L3-001 [138] quotes G. Burgers [152] and CERN 89-08, but also our paper [60]. The Z line shape analysis seems to be based on papers by Cahn [154] and Borrelli et al. [153]. In [139], internal note L3-003, our package ZBIZON is quoted with reference to L3 Internal Note 679 as well as [60] and the Zeuthen preprint PHE 89-19 [98]. Back-up radiative corrections had been studied with ZBIZON. For the very Z line shape fits they used again Borrelli et al. [153], Cahn [154], and a paper by Jadach et al. [83], for Bhabha scattering. In [155], internal note L3-004, the paper on the Z boson parameters [60] was quoted.

A bit later it became more and more common to use ZFITTER in DELPHI and L3, but also in OPAL. While ALEPH used the package BHM/WOH by F. Berends, M. Martinez, W. Hollik et al. [156, 76]. We mention these very first papers on LEP physics results because they demonstrate that there was a true competition of the analysis packages and our ZBIZON/ZFITTER package was accepted step by step, but not from the very beginning.

5.2 1992-2012 - LEPEWWG and global fits

The LEP Electroweak Working Group was founded in 1993.¹⁸ Soon after the first measurements at LEP the quest was expressed for combined data analyses with a fourfold statistics compared to a single experiment. Originally a group with members of the four LEP experiments, led by Jack Steinberger, investigated the combination of the Z line shape [157]. In 1993 Dorothee Schaile was asked to take over the coordination of the group and she had then already ideas on the inclusion of other electroweak observables into a combined analysis. They called themselves the LEP EWWG. The first publicly accessible document with this name is also the initial summary of the LEP results for the electroweak Summer conferences in 1993, which then appeared annually [158 – 160]. The LEP EWWG was lead by D. Schaile from 1993-1996. When she became professor in Munich, Robert Clare took over the coordination of the LEP EEWG.¹⁹ The present chair is Martin Grünewald. The final paper on LEP 1 data appeared in 2005 [25], nearly a decade after closing LEP 1 in 1996, while the analysis of LEP2 data (finalized data taking in 2000) was finished these days [26].

The ZFITTER group members, as well as the authors of other physics software packages used by the LEPEWWG are not members of the LEPEWWG. They are consulted in case.

5.3 1995 – The Electroweak Working Group Report

The work of the LEPEWWG and of the four LEP collaborations relied on ZFITTER and TOPAZ0, and also on the BHM/WOH package, and on many other resources. Because of this role of establishing a kind of world standard, the community felt the need of careful numerical

¹⁷ZBIZON is the former version of ZFITTER.

¹⁸We are grateful to Dorothee Schaile for private information.

¹⁹We are grateful to J. Mnich for a clarification.

checks on their predictions. One is confronted with multi-parameter problems, different calculational schemes, some freedom of input choices, in the presence of approximations and dedicated omissions, of misunderstandings and, sometimes, mistakes.

At a certain moment, the community has to set benchmarks. The result of a year-long workshop is the collection "Reports of the working group on precision calculations for the Z resonance", edited by D. Bardin, W. Hollik, G. Passarino. It was published as a CERN Yellow Report, CERN 95-03 (31 March 1995), <http://cdsweb.cern.ch/record/280836/files/CERN-95-03.pdf>.

Part of this document is the "Electroweak Working Group Report", which was two years later submitted to the arxiv/hep-ph [76].²⁰ This work is one of the basics for the successful work of the LEP Electroweak Working Group. It is until now one of the most important collections of Standard Model higher order corrections for e^+e^- -annihilation.

5.4 Higher order corrections in ZFITTER

During the 1995 CERN workshop and shortly after, a lot of additional higher-order corrections were calculated and included into ZFITTER. We give here just a (presumably not complete) list of references and refer for any detail to the ZFITTER descriptions: [77, 88, 119, 161, 162, 137, 163 – 167]. Later, further improvements were added [168 – 177].

Until now, we did not yet include into ZFITTER the existing parameterization of the rather small *bosonic* two-loop weak corrections to the weak mixing angle [175]. The fermionic corrections are covered, as well as the complete weak two-loop corrections to the W boson mass. For a complete treatment of the weak two-loop corrections to the Z boson width, the corrections to the form factor ρ_Z are lacking yet. For this reason, the quite good agreement of the higher-order *approximations* to Γ_Z with the so far known pieces of the *complete* two-loop result are an indication that the final answer will be close to what we have already.

Generally speaking, we try to control about four to five digits of the predictions aiming at such a *physical* theory precision. One quote from the report [76] is interesting because it sheds some light on the progress of the so-called *technical* precision (precision under fixed, maybe not realistic conditions): “... compare results of independent calculations. Such a comparison has been done once for Δr , and an agreement of up to 12 digits (computer precision) was found [14].” Ref. [14] was private communications of D. Bardin, B. Kniehl and R. Stuart in 1992. This has to be compared to a three digits agreement between two Bhabha cross section calculations in a comparison, performed few years earlier in 1990 [62]. Later, in 2002, a precision of up to 12 digits was reached in practice for complete virtual one-loop calculations, and of 5 digits with inclusion of real corrections [32, 178, 179].

6. ZFITTER 2013

6.1 From ZFITTER v.6.42 to ZFITTER v.6.44beta

The most recent publicly available ZFITTER version is ZFITTER v.6.43 (17 June 2008) [12, 13]. It agrees with ZFITTER v.6.42 up to a correction of a non-influential typo and was

²⁰Now it is also available as a pdf file at CERN, in CERN 95-03.

released by the ZFITTER support group (A. Arbuzov, M. Awramik, M. Czakon, A. Freitas, M. Grünewald, K. Mönig, S. Riemann, T. Riemann, see <http://zfitter.com>). The ZFITTER group was reorganized in February 2012 and consists now of A. Akhundov, A. Arbuzov, D. Bardin, P. Christova, L. Kalinovskaya, A. Olshevksy, S. Riemann, T. Riemann.

Recently, we have included into ZFITTER v.6.44beta (20 January 2013) the final results for the $\mathcal{O}(\alpha_s^4)$ QCD corrections to the Z-boson and W-boson quarkonic partial widths and to the so-called R -ratio by P. Baikov et al. [29, 177]. As may be seen from figure 6.1 and from table 6.1, the numerical shifts in the widths amount to less than 0.3 MeV and are thus well below the experimental errors, e.g. at LEP or at an anticipated GigaZ option of an ILC [180].²¹ A fit formula for the complete electroweak two-loop corrections to the W-boson mass [171] was already included in ZFITTER v.6.42. The final exact results for the complete electroweak two-loop corrections to $\sin^2 \theta_{\text{eff}}^{\text{ff}}$ for light fermions f [119] and the two-loop electroweak fermionic corrections to $\sin^2 \theta_{\text{eff}}^{\text{bb}}$ [176] have to be included yet into ZFITTER. They are known to be small corrections compared to the fit formula [174] covered in ZFITTER since v.6.42. Already these corrections are small compared to the present experimental errors for the gauge boson widths, see table 6.1. For the leptonic weak mixing angle, they are of the order of the experimental error: Compare the Particle Data Group value of (1.4) with the last row in table 6.1. The comparison shows even a systematic deviation of the two values. This deviation traces back to the handling of the hadronic contributions to the photonic vacuum polarization. Changing the ZFITTER default by flag setting ALEM=2 into a variable input and setting this to $\Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02750$, produces a shift of the ZFITTER prediction towards the PDG value.²² See the changes shown in table 6.2. Just to mention, the influence of $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$ on the Higgs mass prediction is visualized in figure 1.2, right. Here it is of minor importance, but visible.

Presently, there are controversial positions concerning ZFITTER's 'conditions of use' and the ZFITTER software licence <http://cpc.cs.qub.ac.uk/licence/licence.html> granted to the authors by Elsevier's Computer Physics Communications Program Library - Programs in Physics & Physical Chemistry. For some details see <http://zfitter.com>. Until the issue is settled, actualized versions of ZFITTER will stay at the beta level and cannot be released.

Sooner or later, the LHC is becoming a precision tool and the community feels some steady need of high-precision Standard Model predictions. Both for use in global fits and for specific cross-section predictions, notably of Drell-Yan processes via the Z resonance. This need would become even more pronounced if the ILC project would substantialize [180].

Regrettably, we see today no alternative project to ZFITTER in the field of precision Standard Model predictions. In the mid-nineteen nineties there were three competing (and cooperating) projects at the disposal [76]: BHM/WOH by W. Hollik et al., TOPAZ0 by G. Passarino et al., and ZFITTER by D. Bardin et al. BHM/WOH was available on request, and the latter two are publicly available. To our knowledge, updating and user support have been minimized for TOPAZ0 and BHM/WOH [156].

²¹A detailed numerical study is in preparation [181].

²²Taking into account the uncertainty $\Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02750 \pm 0.00035$ [182], the corresponding predictions in table 6.2 vary: $\Gamma_Z(\mu^+\mu^-)$ by $\pm 6.7 \times 10^{-5}$, Γ_Z by $\pm 1.2 \times 10^{-4}$, $\Gamma_W(l\nu)$ by $\pm 2.2 \times 10^{-4}$, Γ_W by $\pm 2.2 \times 10^{-4}$, M_W by $\pm 7.5 \times 10^{-5}$, $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ by $\pm 5.0 \times 10^{-4}$. The latter is about the value of the the experimental error.

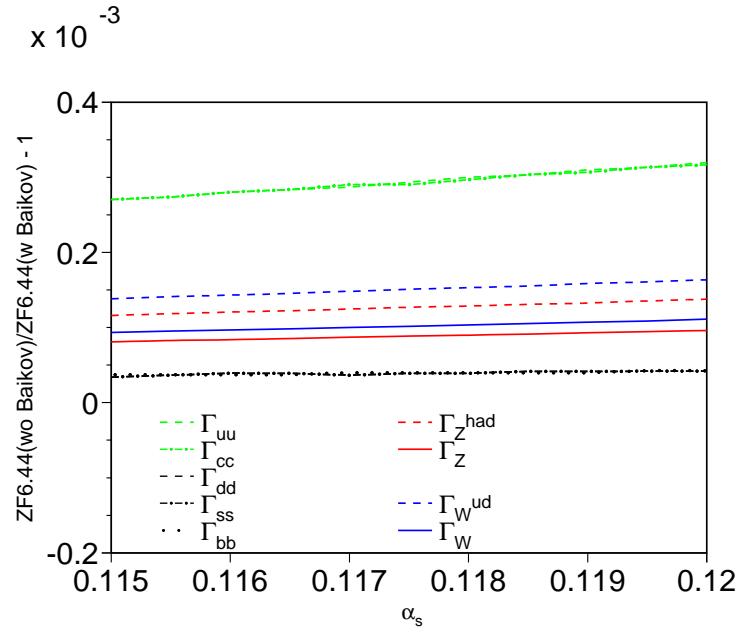


Figure 6.1: The influence of the $\mathcal{O}(\alpha_s^4)$ QCD corrections [177] on the W and Z boson widths.

6.2 A comment on the Gfitter project

Sometimes the Gfitter project is considered as an independent implementation of Standard Model predictions for some pseudo-observables, and as a true scientific alternative to ZFITTER (for these pseudo-observables). We do not share this opinion and would like to give a short, clarifying comment on the situation.

The Gfitter project was started in Summer 2006 and presented to the public in December 2007, at the kick-off meeting of the German “Helmholtz Alliance for Physics at the Terascale”, see the slides at <http://indico.desy.de/materialDisplay.py?contribId=36&sessionId=15&materialId=1&confId=477>. Until August 2012, the Gfitter software was proprietary, but by private information²³ it became known that the Standard Model library of Gfitter, Gfitter/GSM, was relying on the FORTRAN package ZFITTER v.6.42 and was created to a large extent by copy-paste-adapt. Without any proper citation in the academic meaning of the word.

There are several versions of the program Gfitter.

- Gfitter/GSM (Summer 2006 - July 2011) relies essentially and directly on the Standard

²³Private information from and documentation by A. Akhundov, S. Riemann, T. Riemann, March to May 2011, <http://zfitter.com>. Further, a German ombuds person’s report announces in July 2012 : “A diploma thesis derives from ZFITTER in the sense that 8200 lines have been taken over by copying from ZFITTER.” In the thesis work the kernel of the Gfitter/GSM software was written (in collaboration with others), and its text delivered basic building blocks for the so-called main article on Gfitter [183]. A third evidence for the confidential take-overs may be found in the unpublished version of Gfitter of July 2011, where about 100 to 200 identities are denoted, by the Gfitter/GSM authors, to originate from ZFITTER v.6.42. On occasion of the Erratum [184] to [183], ZFITTER authors wrote a letter to the Editorial Board of “European Physical Journal C” (14 September 2012); see [letter-to-the-epjc-editors.pdf](#).

Table 6.1: ZFITTER 6.44beta, with the input values $\alpha_s = 0.1184$, $M_Z = 91.1876$, $M_H = 125$, $m_t = 173$. The dependence on electroweak NNLO corrections is studied for IMOMS=1 (input values are α_{em}, M_Z, G_μ). AMT4= 4: with two-loop sub-leading corrections and re-summation recipe of [23-28] of [13]; AMT4=5: with fermionic two-loop corrections to M_W according to [29,30,32] of [13]; AMT4=6: with complete two-loop corrections to M_W [37] and fermionic two-loop corrections to $\sin^2 \theta_W^{\text{lept,eff}}$ [52] of [13]. IBAIKOV=0 (no α_s^4 QCD corrections) or IBAIKOV=2012 [177].

AMT4	4	5	6	Diff.	Exp. Err.
IBAIKOV=0					
$\Gamma_Z(\mu^+\mu^-)$	83.9782	83.9748	83.9807	0.0059	0.086
Γ_Z	2494.7863	2494.6019	2494.8688	0.2669	2.3
$\Gamma_W(l\nu)$	226.3185	226.2877	226.2922	0.0308	1.9
Γ_W	2090.3308	2090.0465	2090.0882	0.2843	42
M_W	80.3578	80.3541	80.3546	0.0037	0.015
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.231722	0.231791	0.231670	0.000121	0.00012
IBAIKOV=2012					
$\Gamma_Z(\mu^+\mu^-)$	83.9782	83.9748	83.9807	0.0059	0.086
Γ_Z	2494.5591	2494.3747	2494.6416	0.2669	2.3
$\Gamma_W(l\nu)$	226.3185	226.2877	226.2922	0.030	1.9
Γ_W	2090.1117	2089.8274	2089.8691	0.2843	42
M_W	80.3578	80.3541	80.3546	0.0037	0.015
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.231722	0.231791	0.231670	0.000121	0.00012

Model implementation of the ZFITTER software. On top of that, Gfitter/GSM contains few add-ons. The *electroweak add-on* of Gfitter/GSM, compared to ZFITTER v.6.42, are the bosonic two-loop corrections to the weak mixing angle in Amwramik et al. [119]. They are small; see the discussion above. The complete two-loop parameterizations in [119], in turn, have been made with use of ZFITTER v.6.42. As a consequence, it is formally correct to quote for the parameterization only [119], but one should have in mind that there is inside also ZFITTER. There is also a *QCD add-on* of Gfitter/GSM (2011), compared to ZFITTER v.6.42 (2006), based on [185]. It is also numerically small (see the discussion above) and is implemented in ZFITTER v.6.44beta.

Use of this Gfitter version deserves a citation not only of [183], but also of [12, 13], for using ZFITTER v.6.42, according to its licence.

- Gfitter/GSM (August 2011 till August 2012) relies on a proprietary implementation of Standard Model corrections which were based on a parameterization tracing back to Cho et al. (1999) [186], which in turn is based on an electroweak one-loop calculation published in 1994 [187]. There have been made improvements later, and in a recent article by Cho et al. (2011) [188] the authors confirm the reliability of their parametrization by comparing them with ZFITTER v.6.42 predictions. These parameterizations are used in Gfitter furtheron, and overlayed with the most recent higher-order corrections mentioned.

- Gfitter_1.0 has been released publicly in September 2012. The Standard Model library Gfitter_1.0/gew relies presumably on the same parameterizations as Gfitter/GSM (2011).

The different versions of Gfitter rely in one way or the other on ZFITTER v.6.42. We further remark that without studying the numerical reliability of Gfitter, to four or five significant digits, the scientific value of the inclusion of NNLO weak and α_s^4 QCD corrections in Gfitter remains questionable. According to our standards, Gfitter simulates Standard Model predictions with unknown precision. It is a nice tool for the production of figures for the illustration of Standard Model physics. Possibly it is useful for studies beyond the Standard Model.

7. Conclusions

A talk on history and features of the ZFITTER project was presented at LL2012, the eleventh “Loops and Legs” meeting. Its title was “ZFITTER - 20 years after”.²⁴ The “Loops and Legs” conference was founded by the Zeuthen Theory Group in 1992 when the Zeuthen Institute for High Energy Physics of the (then already former) East German Academy of Sciences became part of DESY. We are glad that this conference attracts since then regularly colleagues who contribute to the progress in the field. A field, comprising both the branch of applied calculations and that of development of new theoretical methods.

ZFITTER is certainly one of the oldest source-open software projects in elementary particle physics with a permanent support. It comprises practically all the theoretical knowledge of relevance for a precise description of the Z boson resonance in e^+e^- annihilation and for Z boson’s

Table 6.2: $IBAIKOV=0$ (no α_s^4 QCD corrections) or $IBAIKOV=2012$ [177], AMT4 as described in table 6.1. The difference to table 6.1: Flag ALEM=2 is chosen with input value $\Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02750$.

AMT4	4	5	6	Diff.	Exp. Err.
IBAIKOV=0					
$\Gamma_Z(\mu^+\mu^-)$	83.9875	83.9839	83.9900	0.0061	0.086
Γ_Z	2495.2859	2495.0958	2495.3662	0.2704	2.3
$\Gamma_W(l\nu)$	226.4020	226.3703	226.3745	0.0317	1.9
Γ_W	2091.1020	2090.8092	2090.8474	0.2928	42
M_W	80.3677	80.3639	80.3644	0.0038	0.015
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.231532	0.231603	0.231481	0.000122	0.00012
IBAIKOV=2012					
$\Gamma_Z(\mu^+\mu^-)$	83.9875	83.9839	83.9900	0.0061	0.086
Γ_Z	2495.0586	2494.8685	2495.1389	0.2704	2.3
$\Gamma_W(l\nu)$	226.4020	226.3703	226.3745	0.0317	1.9
Γ_W	2090.8828	2090.5901	2090.6283	0.2927	42
M_W	80.3677	80.3639	80.3644	0.0038	0.015
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.231532	0.231603	0.231481	0.000122	0.00012

²⁴This text is an extended version of the talk. The contribution to the proceedings of LL2012 in “Proceedings of Science” (PoS), by A. Akhundov et al., did not appear: PoS(LL2012)036.

part in global fits in the Standard Model [189]. Certainly, today one would create such a project quite differently. We can only encourage our colleagues to try. Complex projects need (independent) duplication.

Higher order quantum field theoretical predictions face another problem: The solutions become so lengthy and complex that the idea of source-open software is, in practice, no longer a realistic option. This happens already with the $\mathcal{O}(\alpha_s^4)$ QCD corrections and the complete NNLO weak corrections in ZFITTER. They are mere parameterizations of huge, unpublished expressions.

The LEP/SLC era gave the scientific community unprecedented precision in several fundamental quantities like M_Z , Γ_Z , the effective weak mixing angle $\sin^2 \theta_W^{\text{eff}}$, the number of light neutrino flavors N_ν . Of comparable importance is the experimental confirmation of the Standard Model, a gauge theory with spontaneous symmetry breaking, as a consistent quantum field theory, with inclusion of higher orders of perturbation theory.

We are proud that we are being contributing.

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References

- [1] A. Akhundov, D. Bardin, and T. Riemann, *Hunting the hidden standard Higgs*, *Phys. Lett.* **B166** (1986) 111, Dubna preprint JINR-E2-85-454, [doi:10.1016/0370-2693\(86\)91166-4](https://doi.org/10.1016/0370-2693(86)91166-4).
- [2] S. Glashow, *Partial Symmetries of Weak Interactions*, *Nucl. Phys.* **22** (1961) 579–588, [doi:10.1016/0029-5582\(61\)90469-2](https://doi.org/10.1016/0029-5582(61)90469-2).
- [3] S. Weinberg, *A model of leptons*, *Phys. Rev. Lett.* **19** (1967) 1264–1266, [doi:10.1103/PhysRevLett.19.1264](https://doi.org/10.1103/PhysRevLett.19.1264).
- [4] A. Salam, *Weak and Electromagnetic Interactions*, 1968. Originally printed in: Svartholm (ed.), *Elementary Particle Theory*, Proceedings of the Nobel Symposium held 1968 at Lerum, Sweden (Stockholm 1968), p. 367-377; see also: [spires](https://arxiv.org/abs/hep-th/9208013).
- [5] G. 't Hooft and M. Veltman, *Regularization and Renormalization of Gauge Fields*, *Nucl. Phys.* **B44** (1972) 189–213, [doi:10.1016/0550-3213\(72\)90279-9](https://doi.org/10.1016/0550-3213(72)90279-9).
- [6] **Particle Data Group** Collaboration, C. Wohl *et al.*, *Review of Particle Properties*, *Rev. Mod. Phys.* **56** (1984) S1–S304, [doi:10.1103/RevModPhys.56.S1](https://doi.org/10.1103/RevModPhys.56.S1).

- [7] LEP Electroweak Working Group (LEPEWWG), webpage <http://lepewwg.web.cern.ch/LEPEWWG/>.
- [8] **Particle Data Group** Collaboration, J. Beringer *et al.*, *Review of Particle Physics (RPP)*, *Phys.Rev.* **D86** (2012) 010001, doi:[10.1103/PhysRevD.86.010001](https://doi.org/10.1103/PhysRevD.86.010001).
- [9] D. Bardin, M. Bilenky, G. Mitselmakher, T. Riemann, and M. Sachwitz, *A realistic approach to the standard Z peak*, *Z. Phys.* **C44** (1989) 493, scan: [KEK](https://doi.org/10.1007/BF01415565). doi:[10.1007/BF01415565](https://doi.org/10.1007/BF01415565).
- [10] D. Y. Bardin, M. S. Bilenky, T. Riemann, M. Sachwitz, and H. Vogt, *DIZET: A program package for the calculation of electroweak one loop corrections for the process $e^+e^- \rightarrow f^+f^-$ around the Z^0 peak*, *Comput. Phys. Commun.* **59** (1990) 303–312. doi:[10.1016/0010-4655\(90\)90179-5](https://doi.org/10.1016/0010-4655(90)90179-5).
- [11] D. Bardin, M. Bilenky, A. Chizhov, O. Fedorenko, S. Ganguli, A. Gurtu, M. Lokajicek, G. Mitselmakher, A. Olshesky, J. Ridky, S. Riemann, T. Riemann, M. Sachwitz, A. Sazonov, A. Schaile, Y. Sedych, I. Sheer, and L. Vertogradov, *ZFITTER: An analytical program for fermion pair production in e^+e^- annihilation*, 1992, preprint CERN/TH.6443, unpublished, [hep-ph/9412201](https://arxiv.org/abs/hep-ph/9412201).
- [12] D. Bardin, M. Bilenky, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann, and T. Riemann, *ZFITTER v.6.21: A semi-analytical program for fermion pair production in e^+e^- annihilation*, *Comput. Phys. Commun.* **133** (2001) 229–395, doi:[10.1016/S0010-4655\(00\)00152-1](https://doi.org/10.1016/S0010-4655(00)00152-1), [[hep-ph/9908433](https://arxiv.org/abs/hep-ph/9908433)].
- [13] A. Arbuzov, M. Awramik, M. Czakon, A. Freitas, M. Grünewald, K. Mönig, S. Riemann, and T. Riemann, *ZFITTER: A Semi-analytical program for fermion pair production in e^+e^- annihilation, from version 6.21 to version 6.42*, *Comput. Phys. Commun.* **174** (2006) 728–758, [[hep-ph/0507146](https://arxiv.org/abs/hep-ph/0507146)]. doi:[10.1016/j.cpc.2005.12.009](https://doi.org/10.1016/j.cpc.2005.12.009).
- [14] G. Montagna, F. Piccinini, O. Nicrosini, G. Passarino, and R. Pittau, *TOPAZ0: A Program for computing observables and for fitting cross-sections and forward - backward asymmetries around the Z^0 peak*, *Comput. Phys. Commun.* **76** (1993) 328–360.
- [15] G. Montagna, O. Nicrosini, G. Passarino, and F. Piccinini, *TOPAZO 2.0: A Program for computing deconvoluted and realistic observables around the Z^0 peak*, *Comput. Phys. Commun.* **93** (1996) 120–126, [[hep-ph/9506329](https://arxiv.org/abs/hep-ph/9506329)].
- [16] G. Montagna, O. Nicrosini, F. Piccinini, and G. Passarino, *TOPAZO 4.0: A new version of a computer program for evaluation of deconvoluted and realistic observables at LEP-1 and LEP-2*, *Comput. Phys. Commun.* **117** (1999) 278–289, [[hep-ph/9804211](https://arxiv.org/abs/hep-ph/9804211)].
- [17] M. Kobayashi and T. Maskawa, *CP Violation in the Renormalizable Theory of Weak Interaction*, *Prog. Theor. Phys.* **49** (1973) 652–657, doi:[10.1143/PTP.49.652](https://doi.org/10.1143/PTP.49.652).
- [18] **CDF** Collaboration, F. Abe *et al.*, *Observation of top quark production in $\bar{p}p$ collisions*, *Phys. Rev. Lett.* **74** (1995) 2626–2631, [[hep-ex/9503002](https://arxiv.org/abs/hep-ex/9503002)].
- [19] **D0** Collaboration, S. Abachi *et al.*, *Observation of the top quark*, *Phys. Rev. Lett.* **74** (1995) 2632–2637, [[hep-ex/9503003](https://arxiv.org/abs/hep-ex/9503003)].
- [20] **ATLAS** Collaboration, G. Aad *et al.*, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett.* **B716** (2012) 1–29, [[1207.7214](https://arxiv.org/abs/1207.7214)].
- [21] **CMS** Collaboration, S. Chatrchyan *et al.*, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett.* **B716** (2012) 30–61, [[1207.7235](https://arxiv.org/abs/1207.7235)].

- [22] P. W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, *Phys. Rev. Lett.* **13** (1964) 508–509, doi:[10.1103/PhysRevLett.13.508](https://doi.org/10.1103/PhysRevLett.13.508).
- [23] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, *Phys. Lett.* **12** (1964) 132–133, doi:[10.1016/0031-9163\(64\)91136-9](https://doi.org/10.1016/0031-9163(64)91136-9).
- [24] J. Mnich, *Experimental tests of the standard model in $e^+e^- \rightarrow f\bar{f}$ at the Z resonance*, *Phys. Rept.* **271** (1996) 181–266, doi:[10.1016/0370-1573\(95\)00072-0](https://doi.org/10.1016/0370-1573(95)00072-0).
- [25] **ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group** Collaboration, S. Schael *et al.*, *Precision electroweak measurements on the Z resonance*, *Phys. Rept.* **427** (2006) 257–454, [[hep-ex/0509008](https://arxiv.org/abs/hep-ex/0509008)].
- [26] **ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, LEP Electroweak Working Group** Collaboration, S. Schael *et al.*, *Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP*, [1302.3415](https://arxiv.org/abs/1302.3415).
- [27] ICFA Study Group on Data Preservation and Long Term Analysis in High Energy Physics, webpage <http://www.dphhep.org/>.
- [28] K. Wichmann, *DESY Data Preservation Project*, talk held at CHEP2012, [DDPP](https://arxiv.org/abs/1206.1526).
- [29] A. Arbuzov *et al.*, ZFITTER v.6.44beta (20 January 2013), references [[12](#), [13](#)] and private communication T. Riemann.
- [30] D. Y. Bardin, *Twelve years of precision calculations for LEP. What's next?*, *J. Phys.* **G29** (2003) 75–82, [[hep-ph/0101295](https://arxiv.org/abs/hep-ph/0101295)].
- [31] D. Y. Bardin, L. Kalinovskaya, and G. Nanava, *An electroweak library for the calculation of EWRC to $e^+e^- \rightarrow f\bar{f}$ within the tofit project*, [hep-ph/0012080](https://arxiv.org/abs/hep-ph/0012080).
- [32] J. Fleischer, T. Hahn, W. Hollik, T. Riemann, C. Schappacher, and A. Werthenbach, *Complete electroweak one loop radiative corrections to top pair production at TESLA: A Comparison*, [hep-ph/0202109](https://arxiv.org/abs/hep-ph/0202109).
- [33] J. Fleischer, A. Leike, T. Riemann, and A. Werthenbach, *Electroweak one loop corrections for e^+e^- annihilation into $t\bar{t}$ including hard bremsstrahlung*, *Eur. Phys. J.* **C31** (2003) 37–56, [[hep-ph/0302259](https://arxiv.org/abs/hep-ph/0302259)].
- [34] W. Beenakker, *Electroweak corrections: Techniques and applications*, Ph.D. thesis, Univ. Leiden, 1989. For print on demand see: [NTIS - U.S. Department of Commerce, National Technical Information Service](#).
- [35] D. Bardin and O. Fedorenko, *On high order effects for fermion elastic scattering processes in Weinberg-Salam theory. 1. Renormalization scheme*, Dubna preprint JINR-P2-11413 (1978), unpublished, scan: [JINR-P2-11413.pdf](#).
- [36] D. Bardin and O. Fedorenko, *On high order effects for fermion elastic scattering processes in Weinberg-Salam theory. 2. Calculation of one loop diagrams*, Dubna preprint JINR-P2-11414 (1978), unpublished, scan: [JINR-P2-11414.pdf](#).
- [37] D. Bardin and O. Fedorenko, *The one-loop approximation for the amplitude of the process $\nu_l q_1 \rightarrow l q_2$ in the Weinberg-Salam theory (in Russian)*, Dubna preprint JINR-P2-11461 (1978), unpublished, scan: [JINR-P2-11461.pdf](#).
- [38] D. Bardin, P. Khristova, and O. Fedorenko, *On the lowest order electroweak corrections to spin 1/2 fermion scattering. 1. The one loop diagrammar*, *Nucl. Phys.* **B175** (1980) 435. doi:[10.1016/0550-3213\(80\)90021-8](https://doi.org/10.1016/0550-3213(80)90021-8).

- [39] D. Y. Bardin, P. K. Khristova, and O. Fedorenko, *On the lowest order electroweak corrections to spin 1/2 fermion scattering. 2. The one loop amplitudes*, *Nucl. Phys.* **B197** (1982) 1.
[doi:10.1016/0550-3213\(82\)90152-3](https://doi.org/10.1016/0550-3213(82)90152-3).
- [40] D. Bardin, O. Fedorenko, and P. Khristova, *One loop effects in Weinberg-Salam theory. In Russian*, *Yad. Fiz.* **35** (1982) 1220–1230.
- [41] D. Bardin and P. Khristova, “*Electroweak one loop corrections to amplitudes of fermion annihilation into a neutral vector boson pair.*” Dubna preprint JINR-P2-82-836 (1982), unpublished.
- [42] D. Bardin, O. Fedorenko, and P. Khristova, “*On the lowest order electroweak corrections to fermion - boson scattering. Selfenergy and vertex diagrams.*” Dubna preprint JINR-P2-82-840 (1982), unpublished.
- [43] A. Akhundov, D. Bardin, and T. Riemann, *Electroweak One Loop Corrections to the Decay of the Neutral Vector Boson*, *Nucl. Phys.* **B276** (1986) 1, [doi:10.1016/0550-3213\(86\)90014-3](https://doi.org/10.1016/0550-3213(86)90014-3).
- [44] D. Bardin, S. Riemann, and T. Riemann, *Electroweak one loop corrections to the decay of the charged vector boson*, *Z. Phys.* **C32** (1986) 121–125, [doi:10.1007/BF01441360](https://doi.org/10.1007/BF01441360).
- [45] P. K. Khristova, *The one loop effects in the electroweak Glashow-Weinberg-Salam theory*, *Acta Phys. Polon.* **B18** (1987) 3–20.
- [46] H. Czyz, K. Kolodziej, M. Zralek, and P. Khristova, *Is the anapole moment a physical observable?*, *Can. J. Phys.* **66** (1988) 132–134.
- [47] G. Mann and T. Riemann, *On mass shell renormalization of the Weinberg-Salam theory: An introductory lecture*, 1983. Zeuthen preprint PHE 83-09, 91 pages, unpublished, scan: lfvz-intro.html.
- [48] G. Mann and T. Riemann, *Particle mixing and renormalization in the Weinberg-Salam theory*, talk at ‘Symposium Ahrenschoop 1981 on Special Topics In Gauge Field Theories’, PHE 81-07, p. 88-91, scan: lfvz-intro.html.
- [49] G. Mann and T. Riemann, *Muon number nonconserving decay of a heavy neutral gauge boson*, Zeuthen preprint PHE 82-5 (1982), scan: lfvz-intro.html.
- [50] G. Mann and T. Riemann, *Nondiagonal Z decay: $Z \rightarrow e\mu$* , talk held at ‘Neutrino ’82’, Balatonfured, Hungary, 1982, published in the proceedings, vol. 2, p. 58-61, scan: lfvz-intro.html.
- [51] G. Mann and T. Riemann, *Effective flavor changing weak neutral current in the standard theory and Z boson decay*, *Annalen Phys.* **40** (1984) 334, Zeuthen preprint PHE 83-03, scan: [KEK](http://kek.org).
- [52] J. I. Illana and T. Riemann, *Charged lepton flavour violation from massive neutrinos in Z decays*, *Phys. Rev.* **D63** (2001) 053004, [[hep-ph/0010193](https://arxiv.org/abs/hep-ph/0010193)].
- [53] J. I. Illana and M. Masip, *Lepton flavor violation in Z and lepton decays in supersymmetric models*, *Phys. Rev.* **D67** (2003) 035004, [[hep-ph/0207328](https://arxiv.org/abs/hep-ph/0207328)].
- [54] A. Sirlin and A. Ferroglia, *Radiative Corrections in Precision Electroweak Physics: a Historical Perspective*, [1210.5296](https://arxiv.org/abs/1210.5296).
- [55] D. Bardin, C. Burdick, P. Khristova, and T. Riemann, *Electroweak radiative corrections to deep inelastic scattering at HERA. Neutral current scattering*, *Z. Phys.* **C42** (1989) 679,
[doi:10.1007/BF01557676](https://doi.org/10.1007/BF01557676).

- [56] A. Arbuzov, D. Y. Bardin, J. Blümlein, L. Kalinovskaya, and T. Riemann, *Hector 1.00: A Program for the calculation of QED, QCD and electroweak corrections to $e p$ and lepton+-N deep inelastic neutral and charged current scattering*, *Comput. Phys. Commun.* **94** (1996) 128–184, [[hep-ph/9511434](#)].
- [57] D. Bardin, M. Bilenky, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann, and T. Riemann, *ZFITTER v.6.21: A semi-analytical program for fermion pair production in e^+e^- annihilation*, *Comput. Phys. Commun.* **133** (2001) 229–395, [[hep-ph/9908433](#)].
- [58] D. Y. Bardin and O. Fedorenko, *Evaluation of systematic uncertainties caused by radiative corrections in experiments on deep inelastic lepton neutrino n scattering*, *Sov. J. Nucl. Phys.* **30** (1979) 418, scan: [KEK](#).
- [59] D. Y. Bardin, O. Fedorenko, and N. Shumeiko, *On the radiative corrections to p odd asymmetry in deep inelastic scattering of polarized leptons on nucleons*, *Sov. J. Nucl. Phys.* **32** (1980) 403, scan: [KEK](#).
- [60] D. Bardin, A. Leike, T. Riemann, and M. Sachwitz, *Energy dependent width effects in e^+e^- annihilation near the Z boson pole*, *Phys. Lett.* **B206** (1988) 539–542. doi:10.1016/0370-2693(88)91625-5.
- [61] S. Riemann, *A Comparison of programs used in L3 for the analysis of Bhabha scattering*, 1991, PHE-91-04, unpublished, scan: [KEK](#).
- [62] D. Bardin, W. Hollik, and T. Riemann, *Bhabha scattering with higher order weak loop corrections*, *Z. Phys.* **C49** (1991) 485–490, doi:10.1007/BF01549702.
- [63] J. Field and T. Riemann, *BHAGENE3: A Monte Carlo event generator for lepton pair production and wide angle Bhabha scattering in e^+e^- collisions near the Z peak*, *Comput. Phys. Commun.* **94** (1996) 53–87, [[hep-ph/9507401](#)].
- [64] D. Bardin, Burdick, K., P. Khristova, and T. Riemann, *Electroweak radiative corrections to deep inelastic scattering at HERA. charged current scattering*, *Z. Phys.* **C44** (1989) 149, doi:10.1007/BF01548593.
- [65] D. Bardin, S. Jadach, T. Riemann, and Z. Was, *Predictions for $\bar{\nu}\nu\gamma$ production at LEP*, *Eur. Phys. J.* **C24** (2002) 373–383, [[hep-ph/0110371](#)].
- [66] D. Y. Bardin, P. Christova, L. Kalinovskaya, and G. Passarino, *Atomic parity violation and precision physics*, *Eur. Phys. J.* **C22** (2001) 99–104, [[hep-ph/0102233](#)].
- [67] A. Leike, S. Riemann, and T. Riemann, *ZZ' mixing in presence of standard weak loop corrections*, [hep-ph/9808374](#). Unpublished preprint LMU-91/06, L3 note # 1074, [CERN library copy](#).
- [68] W. Wetzel, *Electroweak radiative corrections for $e^+e^- \rightarrow \mu^+\mu^-$ at LEP energies*, *Nucl. Phys.* **B227** (1983) 1, doi:10.1016/0550-3213(83)90139-6.
- [69] B. Lynn and R. Stuart, *Standard model electroweak radiative corrections to longitudinal polarization asymmetry A_{Pol} and forward-backward asymmetry A_{FB} in $e^+e^- \rightarrow \mu^+\mu^-$ on and off the Z^0 resonance*, *Nucl. Phys.* **B253** (1985) 216, doi:10.1016/0550-3213(85)90528-0.
- [70] F. A. Berends, R. Kleiss, and S. Jadach, *Radiative corrections to muon pair and quark pair production in electron-positron collisions in the Z^0 region*, *Nucl. Phys.* **B202** (1982) 63, doi:10.1016/0550-3213(82)90221-8.
- [71] D. Bardin and N. Shumeiko, *An Exact Calculation of the Lowest Order Electromagnetic Correction to the Elastic Scattering*, *Nucl. Phys.* **B127** (1977) 242. doi:10.1016/0550-3213(77)90213-9.

- [72] A. A. Akhundov, D. Y. Bardin, L. Kalinovskaya, and T. Riemann, *Model independent QED corrections to the process $ep \rightarrow eX$* , *Fortsch. Phys.* **44** (1996) 373–482, [[hep-ph/9407266](#)].
- [73] A. Akhundov, D. Bardin, O. Fedorenko, and T. Riemann, “Some integrals for exact calculation of QED bremsstrahlung.” Dubna preprint JINR-E2-84-777, unpublished, scan: [KEK](#).
- [74] A. Akhundov, D. Y. Bardin, O. Fedorenko, and T. Riemann, *Exact calculations of the lowest order electromagnetic corrections for the processes $e^+e^- \rightarrow \mu^+\mu^- (\tau^+\tau^-)$* , *Sov. J. Nucl. Phys.* **42** (1985) 762, scan: [KEK](#).
- [75] O. Fedorenko and T. Riemann, *Analytic bremsstrahlung integration for the process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ in QED*, *Acta Phys. Polon.* **B18** (1987) 761, scan: [KEK](#).
- [76] D. Bardin, W. Beenakker, M. Bilenky, W. Hollik, M. Martinez, G. Montagna, O. Nicrosini, V. Novikov, L. Okun, A. Olshevsky, G. Passarino, F. Piccinini, S. Riemann, T. Riemann, A. Rozanov, F. Teubert, and M. Vysotsky, *Electroweak working group report*, [hep-ph/9709229](#). The report is part of: D. Bardin, W. Hollik, G. Passarino (eds.), Reports of the working group on precision calculations for the Z resonance, CERN 95-03 (31 March 1995).
- [77] K. Chetyrkin, J. H. Kühn, and A. Kwiatkowski, *QCD corrections to the e^+e^- cross-section and the Z boson decay rate*, [hep-ph/9503396](#). Published in ‘Reports of the working group on precision calculations for the Z resonance’, p. 175-263 (Geneva 1994), CERN 95-03 (31 March 1995). See also: ‘QCD corrections to the e^+e^- cross-section and the Z boson decay rate: Concepts and results’, March 1996, 105 pages, LBL-36678-REV and *Phys. Rept.* **277** (1996) 189-281.
- [78] D. Bardin, M. Grünewald, and G. Passarino, *Precision calculation project report*, [hep-ph/9902452](#).
- [79] D. Y. Bardin and G. Passarino, *The standard model in the making: Precision study of the electroweak interactions*, Oxford University Press, 1999. International series of monographs on physics, 104; [Amazon](#).
- [80] W. Beenakker, F. A. Berends, and W. van Neerven, *Applications of renormalization group methods to radiative corrections*, . Presented at Workshop on Electroweak Radiative Corrections, Ringberg Castle, Germany, Apr 3-7, 1989, scan: [KEK](#).
- [81] F. A. Berends and R. Kleiss, *Distributions in the process $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$* , *Nucl. Phys.* **B177** (1981) 237, doi:[10.1016/0550-3213\(81\)90390-4](#).
- [82] S. Jadach, J. H. Kühn, and Z. Was, *TAUOLA: A Library of Monte Carlo programs to simulate decays of polarized tau leptons*, *Comput. Phys. Commun.* **64** (1990) 275–299, doi:[10.1016/0010-4655\(91\)90038-M](#).
- [83] S. Jadach, B. Ward, and Z. Was, *The Monte Carlo program KORALZ, version 3.8, for the lepton or quark pair production at LEP / SLC energies*, *Comput. Phys. Commun.* **66** (1991) 276–292, doi:[10.1016/0010-4655\(91\)90077-X](#).
- [84] G. Montagna, F. Piccinini, and O. Nicrosini, *Structure function formulation of $e^+e^- \rightarrow f\bar{f}$ around the Z^0 resonance in realistic setup*, *Phys. Rev.* **D48** (1993) 1021–1034, doi:[10.1103/PhysRevD.48.1021](#).
- [85] S. Jadach, B. Ward, and Z. Was, *The precision Monte Carlo event generator KK for two-fermion final states in e^+e^- collisions*, *Comput. Phys. Commun.* **130** (2000) 260–325, doi:[10.1016/S0010-4655\(00\)00048-5](#), [[hep-ph/9912214](#)].
- [86] G. Altarelli, R. Kleiss, C. Verzegnassi (Eds.). *Z physics at LEP1: Event generators and software*, report [CERN-89-08-V-3.pdf](#).

- [87] T. Riemann, M. Sachwitz, and D. Bardin, “The Z boson line shape at LEP.” Contribution to XI Warsaw symposium on elementary particle physics: New theories in physics, 23-27 May 1988, Kazimierz, Poland; proceedings edited by Z. Ajduk, S. Pokorski, A. Trautman (Teaneck, N.J., World Scientific, 1988), p. 238-246, scan: [KEK](#).
- [88] M. Consoli, W. Hollik, and F. Jegerlehner, *The Effect of the Top Quark on the $M(W)$ - $M(Z)$ Interdependence and Possible Decoupling of Heavy Fermions from Low-Energy Physics*, *Phys.Lett. B* **227** (1989) 167, doi:[10.1016/0370-2693\(89\)91301-4](#).
- [89] F. A. Berends, R. Kleiss, and S. Jadach, *Monte Carlo simulation of radiative corrections to the processes $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \bar{q}q$ in the Z^0 region*, *Comput. Phys. Commun.* **29** (1983) 185–200, [10.1016/0010-4655\(83\)90073-5](#).
- [90] D. Bardin, O. Fedorenko, and T. Riemann, *The electromagnetic α^3 contributions to e^+e^- annihilation into fermions in the electroweak theory. Total cross-section σ_t and integrated asymmetry A_{FB}* , 1987, Dubna preprint JINR-E2-87-663, unpublished, scan: [KEK](#).
- [91] D. Bardin, M. Bilenky, O. Fedorenko, and T. Riemann, *The electromagnetic α^3 contributions to e^+e^- annihilation into fermions in the electroweak theory. Total cross-section σ_t and integrated asymmetry A_{FB}* , 1988, Dubna preprint JINR-E2-88-324, unpublished, scan: [KEK](#).
- [92] A. Leike, T. Riemann, and M. Sachwitz, *QED corrected extra Z boson effects at e^+e^- colliders*, *Phys. Lett. B* **241** (1990) 267, doi:[10.1016/0370-2693\(90\)91291-I](#).
- [93] A. Leike and T. Riemann, *QED corrections to the forward backward asymmetry with extra Z bosons for $e^+e^- \rightarrow f^+f^-$* , *Z. Phys.* **C51** (1991) 113–118, doi:[10.1007/BF01579567](#).
- [94] A. Djouadi, A. Leike, T. Riemann, D. Schaile, and C. Verzegnassi, *Signals of new gauge bosons at future e^+e^- colliders*, *Z. Phys.* **C56** (1992) 289–300, doi:[10.1007/BF01555527](#).
- [95] **L3** Collaboration, O. Adriani *et al.*, *Search for a Z' at the Z resonance*, *Phys. Lett. B* **306** (1993) 187–196, doi:[10.1016/0370-2693\(93\)91156-H](#).
- [96] S. Riemann, *Suche nach einem Z' -Boson auf der Z-Resonanz mit dem L3-Detektor am LEP-Beschleuniger*, Dissertation, Technische Hochschule Aachen (1994), 94 S., Internal Report: DESY-Zeuthen 94-01, September 1994.
- [97] D. Bardin, M. Bilenky, A. Chizhov, A. Sazonov, Y. Sedykh, T. Riemann, and M. Sachwitz, *The convolution integral for the forward-backward asymmetry in e^+e^- annihilation*, *Phys. Lett. B* **229** (1989) 405. doi:[10.1016/0370-2693\(89\)90428-0](#).
- [98] D. Bardin, M. Bilenky, A. Chizhov, A. Sazonov, A. Sazonov, O. Fedorenko, T. Riemann, and M. Sachwitz, *Analytic approach to the complete set of QED corrections to fermion pair production in e^+e^- annihilation*, *Nucl. Phys. B* **351** (1991) 1–48, [[hep-ph/9801208](#)].
- [99] D. Bardin, M. Bilenky, A. Sazonov, Y. Sedykh, Y. Sedykh, T. Riemann, and M. Sachwitz, *QED corrections with partial angular integration to fermion pair production in e^+e^- annihilation*, *Phys. Lett. B* **255** (1991) 290–296, [[hep-ph/9801209](#)].
- [100] M. Bilenky and A. Sazonov, *QED corrections at Z^0 pole with realistic kinematical cuts*, 1989. Dubna preprint JINR-E2-89-792, unpublished, scan: [KEK](#).
- [101] G. Passarino, *Hard bremsstrahlung corrections for the process $e^+e^- \rightarrow \mu^+\mu^-$* , *Nucl. Phys. B* **204** (1982) 237–266. doi:[10.1016/0550-3213\(82\)90147-X](#).

- [102] P. Christova, M. Jack, S. Riemann, and T. Riemann, *Predictions of ZFITTER v.6 for fermion pair production with acollinearity cut*, [hep-ph/9908289](#). DESY-99-037, 1999, unpublished, based on talks presented at ECFA/DESY Linear Collider Project Meetings at Frascati, November 1998 and Oxford, March 1999 and at LEP 2 Miniworkshop at CERN, March 1999 and at Workshop for a Worldwide Study on Physics and Experiments with Future Linear e^+e^- Colliders at Sitges/Barcelona, April 1999.
- [103] P. Christova, M. Jack, S. Riemann, and T. Riemann, *Radiative corrections to $e^+e^- \rightarrow \bar{f}f$* , [hep-ph/0002054](#). Linear Collider Note LC-TH-2000-008.
- [104] P. Christova, M. Jack, S. Riemann, and T. Riemann, *Predictions for fermion pair production at LEP*, [hep-ph/9812412](#). Published in Proceedings of RADCOR, 8-12 Sep 1998, Barcelona, Catalonia, Spain.
- [105] M. A. Jack, *Semianalytical calculation of QED radiative corrections to $e^+e^- \rightarrow \bar{f}f$ with special emphasis on kinematical cuts to the final state*, [hep-ph/0009068](#). DESY-THESIS-2000-030.
- [106] P. Christova, M. Jack, and T. Riemann, *Hard photon emission in $e^+e^- \rightarrow \bar{f}f$ with realistic cuts*, *Phys. Lett.* **B456** (1999) 264–269, [[hep-ph/9902408](#)].
- [107] H. Strubbe, *Manual for Schoonschip: A CDC 6000 / 7000 program for symbolic evaluation of algebraic expressions*, *Comput. Phys. Commun.* **8** (1974) 1–30 doi:[10.1016/0010-4655\(74\)90081-2](#).
- [108] M. J. Veltman and D. N. Williams, *Schoonschip '91*, [hep-ph/9306228](#).
- [109] R. N. Fedorova, V. P. Gerdt, N. N. Govorun and V. P. Shirikov, *Computer algebra in physical research of JINR*, talk at ‘Eurocal 87’, European Conference on Computer Algebra, Leipzig, GDR, June 2-5, 1987. Published in: Lecture Notes in Computer Science Volume 378 (1989), p. 1-10, doi:[10.1007/3-540-51517-8_80](#), scan: Springer.
- [110] J. Vermaseren. “Symbolic manipulation with FORM, Version 2” (Computer Algebra Nederland, Amsterdam, 1991).
- [111] J. Vermaseren, *New features of FORM*, [math-ph/0010025](#).
- [112] F. A. Berends, G. Burgers, W. Hollik, and W. L. van Neerven, *The standard Z peak*, *Phys. Lett.* **B203** (1988) 177, doi:[10.1016/0370-2693\(88\)91593-6](#).
- [113] A. Leike, T. Riemann, and J. Rose, *S matrix approach to the Z line shape*, *Phys. Lett.* **B273** (1991) 513–518, [[hep-ph/9508390](#)].
- [114] T. Riemann, *Cross-section asymmetries around the Z peak*, *Phys. Lett.* **B293** (1992) 451–456, [[hep-ph/9506382](#)].
- [115] S. Kirsch and S. Riemann, “A Combined Fit to the L3 Data Using the S-Matrix Approach (First Results).” L3 note 1233, 1992, <http://l3.web.cern.ch/l3/note/notes1992.html>.
- [116] S. Kirsch and S. Riemann, “L3 Results of model-independent Analyses.” L3 note 1656, 1994, <http://l3.web.cern.ch/l3/note/notes1994.html>.
- [117] L3 Collaboration, O. Adriani *et al.*, *An S matrix analysis of the Z resonance*, *Phys. Lett.* **B315** (1993) 494–502, doi:[10.1016/0370-2693\(93\)91646-5](#). L3 note 1462, preprint EXP L3 #062.
- [118] S. Kirsch and T. Riemann, *SMATASY: A program for the model independent description of the Z resonance*, *Comput. Phys. Commun.* **88** (1995) 89–108, [[hep-ph/9408365](#)].
- [119] M. Awramik, M. Czakon, and A. Freitas, *Electroweak two-loop corrections to the effective weak mixing angle*, *JHEP* **0611** (2006) 048, [[hep-ph/0608099](#)].

- [120] A. Akhundov, D. Y. Bardin, and A. Leike, *QED radiative corrections to massive fermion production in e^+e^- annihilation*, *Phys. Lett.* **B261** (1991) 321–325, doi:[10.1016/0370-2693\(91\)90335-N](https://doi.org/10.1016/0370-2693(91)90335-N).
- [121] A. Arbuzov, D. Y. Bardin, and A. Leike, *Analytic final state corrections with cut for $e^+e^- \rightarrow$ massive fermions*, *Mod. Phys. Lett.* **A7** (1992) 2029–2038, E: **A9** (1994) 1515, scan: [KEK](#), doi:[10.1142/S0217732392001762](https://doi.org/10.1142/S0217732392001762).
- [122] M. Jack, A. Höfer, A. Leike, and T. Riemann, *Predictions for fermion pair production at e^+e^- colliders*, *Nucl. Phys. Proc. Suppl.* **89** (2000) 15–24, Contribution to Proceedings of Loops and legs in quantum field theory, LL2000, 9–14 Apr 2000, Koenigstein–Weissig, Germany, *Nucl. Phys. Proc. Suppl.* **89** (2000) 15–24 [[190](#)], [[hep-ph/0007046](#)].
- [123] A. Arbuzov, *Light pair corrections to electron positron annihilation at LEP/SLC*, [hep-ph/9907500](#).
- [124] A. Arbuzov, *Nonsinglet splitting functions in QED*, *Phys. Lett.* **B470** (1999) 252–258, doi:[10.1016/S0370-2693\(99\)01290-3](https://doi.org/10.1016/S0370-2693(99)01290-3), [[hep-ph/9908361](#)].
- [125] F. Boudjema, B. Mele, E. Accomando, S. Ambrosanio, A. Ballestrero, D. Lehner, *et al.*, *Standard model processes*, [hep-ph/9601224](#). Published in ‘Physics at LEP 2’, vol. 1, p.207-248.
- [126] D. Y. Bardin and G. Passarino, *Upgrading of precision calculations for electroweak observables*, [hep-ph/9803425](#).
- [127] **Two Fermion Working Group** Collaboration, M. Kobel, Z. Was, *et al.*, *Two-fermion production in electron positron collisions*, CERN 2000-009-D, contrib. to the LEP 2 Monte Carlo Workshop 1999/2000, [hep-ph/0007180](#).
- [128] T. Riemann, M. Sachwitz, D. Bardin, and M. Bilenky, “On the derivation of standard model parameters from the Z peak.” Presented at ‘Workshop on Electroweak Radiative Corrections’, 3-7 April 1989, Ringberg, Germany; Proceedings: ‘Radiative corrections for e^+e^- collisions’, edited by J.H. Kühn (Berlin, Germany, Springer-Verlag, 1989) 349 p; scan: [KEK](#).
- [129] D. Bardin and T. Riemann, *electroweak radiative corrections at the Z peak*, presented at RADCOR1989, ‘Workshop On Radiative Corrections: Results And Perspectives’, 9-14 Jul 1989, Brighton, England; proceedings edited by N. Dombey and F. Boudjema (N.Y., Plenum Press, 1990), NATO Advanced Study Institute, Series B: Physics, vol. 233, p. 169-184, preprint PHE-89-11, scan: [KEK](#).
- [130] M. Böhm, W. Hollik, M. Igarashi, F. Jegerlehner, T. Riemann, and B. Ward, “Report on working group A: Renormalization schemes for electroweak radiative corrections.” Presented at RADCOR1989, ‘Workshop On Radiative Corrections: Results And Perspectives’, 9-14 Jul 1989, Brighton, England; proceedings edited by N. Dombey and F. Boudjema (N.Y., Plenum Press, 1990) 578 p., NATO Advanced Study Institute, Series B: Physics, v. 233, p. 233-243, scan: [radcor1989-boehm-et-al.pdf](#).
- [131] M. Böhm, W. Hollik, D. Bardin, W. Beenakker, F. Berends, S. Bilenky, G. Burgers, J. Campagne, A. Djouadi, O. Fedorenko, S. Jadach, G. Montagna, O. Nicrosini, T. Riemann, M. Sachwitz, L. Trentadue, W. van Neerven, Z. Was, and R. Zitoun, *Forward-backward asymmetries*, . in: CERN Yellow Report 89-08, preprint CERN/TH. 5536, [KEK scan](#).
- [132] R. Leiste, T. Riemann, M. Sachwitz, H. Vogt, D. Bardin, M. Bilenky, and G. Mitselmakher, “Precise measurement of M_Z and I_Z^2 from the Z peak: A contribution to the running strategy of LEP 1.” Zeuthen preprint PHE-89-02, 1989, unpublished, scan: [KEK](#).

- [133] D. Bardin, L. Vertogradov, Y. Sedykh, and T. Riemann, “On some new analytic calculations for the process $e^+e^- \rightarrow \bar{f}f(n\gamma)$.” CERN-TH-5434/89, 1989, unpublished, scan: [KEK](#).
- [134] M. S. Bilenky and M. Sachwitz, “The forward-backward asymmetry A_{FB} in e^+e^- annihilation.” Zeuthen preprint PHE-89-10, unpublished, scan: [KEK](#).
- [135] D. Bardin and A. Chizhov. *On the $O(\alpha_{em}\alpha_s)$ corrections to electroweak observables*, in: D. Bardin et al. (Eds.), Proc. Int. Topical Seminar on Physics of e^+e^- Interactions at LEP energies, 15-16 Nov. 1988, JINR Dubna, USSR, JINR preprint E2-89-525, 1989, pp. 42-48.
- [136] A. Djouadi, *$O(\alpha\alpha_s)$ vacuum polarization functions of the standard model gauge bosons*, *Nuovo Cim.* **A100** (1988) 357, doi:[10.1007/BF02812964](#).
- [137] B. A. Kniehl, *Two loop corrections to the vacuum polarizations in perturbative QCD*, *Nucl. Phys.* **B347** (1990) 86–104, doi:[10.1016/0550-3213\(90\)90552-O](#).
- [138] **L3** Collaboration, B. Adeva et al., *A Determination of the Properties of the Neutral Intermediate Vector Boson Z^0* , *Phys. Lett.* **B231** (1989) 509, scan: [CERN](#).
- [139] **L3** Collaboration, B. Adeva et al., *Measurement of $g(a)$ and $g(v)$, the neutral current coupling constants to leptons*, *Phys. Lett.* **B236** (1990) 109, scan: [lib.umich.edu](#).
- [140] **L3** Collaboration, B. Adeva et al., *A measurement of the Z^0 leptonic partial widths and the vector and axial vector coupling constants*, *Phys. Lett.* **B238** (1990) 122–130, doi:[10.1016/0370-2693\(90\)92111-U](#).
- [141] **L3** Collaboration, B. Adeva et al. *A measurement of the Z^0 leptonic partial widths and the forward - backward asymmetry*, internal note L3-005, CALT-68-1617, 1990.
- [142] **L3** Collaboration, B. Adeva et al., *Measurement of $Z^0 \rightarrow b\bar{b}$ decay properties*, *Phys. Lett.* **B241** (1990) 416–424, doi:[10.1016/0370-2693\(90\)91666-Y](#).
- [143] **L3** Collaboration, B. Adeva et al., *A Determination of electroweak parameters from $Z^0 \rightarrow \mu^+\mu^-(\gamma)$* , *Phys. Lett.* **B247** (1990) 473–480, doi:[10.1016/0370-2693\(90\)90926-W](#).
- [144] **L3** Collaboration, B. Adeva et al., *A Precision measurement of the number of neutrino species*, *Phys. Lett.* **B249** (1990) 341–352, doi:[10.1016/0370-2693\(90\)91267-F](#).
- [145] **L3** Collaboration, B. Adeva et al., *A Determination of electroweak parameters from Z^0 decays into charged leptons*, *Phys. Lett.* **B250** (1990) 183–192, doi:[10.1016/0370-2693\(90\)91175-B](#).
- [146] **Delphi** Collaboration, P. Aarnio et al., *Measurement of the Mass and Width of the Z^0 Particle from Multi - Hadronic Final States Produced in e^+e^- Annihilations*, *Phys. Lett.* **B231** (1989) 539, scan: [CERN](#).
- [147] **Delphi** Collaboration, P. Aarnio et al., *Study of hadronic decays of the Z^0 boson*, *Phys. Lett.* **B240** (1990) 271, doi:[10.1016/0370-2693\(90\)90445-C](#).
- [148] **DELPHI** Collaboration, P. Aarnio et al., *Study of the leptonic decays of the Z^0 boson*, *Phys. Lett.* **B241** (1990) 425–434, scan: [CERN](#).
- [149] **DELPHI** Collaboration, P. Abreu et al., *A precise measurement of the Z resonance parameters through its hadronic decays*, *Phys. Lett.* **B241** (1990) 435–448, doi:[10.1016/0370-2693\(90\)91668-2](#).
- [150] **DELPHI** Collaboration, P. Abreu et al., *DELPHI results on the Z^0 resonance parameters through its hadronic and leptonic decay modes*, . Aug 1990, contributed to the Singapore conference 1990, scan: [CERN](#).

- [151] G. Alekseev, D. Bardin, M. S. Bilenky, I. Boyko, G. Chelkov, L. Kalinovskaya, B. Khomenko, N. Khovansky, O. Kuznetsov, Z. Krumshtein, V. Malyshev, M. Nikolenko, A. Olshevsky, V. Pozdnyakov, N. Pukhaeva, A. Sadovsky, Y. Sedykh, A. Sisakian, O. Smirnova, L. Tkachev, I. Tyapkin, L. Vertogradov, A. Vodopianov, N. Zimin, A. Zinchenko, and A. Zinchenko, *The DELPHI experiment at LEP, Part.Nucl.Lett.* **98** (2001) 5–22.
- [152] G. Burgers, *The shape and size of the Z resonance*, . Published in Alexander, G. (ed.) et al.: Polarization at LEP, vol. 1, p. 121–135, preprint CERN-TH. 5119 (1988), 19 p., scan: <http://cds.cern.ch/record/191159/files/CERN-88-06-V-1.pdf>.
- [153] A. Borrelli, M. Consoli, L. Maiani, and R. Sisto, *Model independent analysis of the Z line shape in e^+e^- annihilation*, *Nucl. Phys.* **B333** (1990) 357, doi:[10.1016/0550-3213\(90\)90042-C](https://doi.org/10.1016/0550-3213(90)90042-C).
- [154] R. N. Cahn, *Analytic forms for the e^+e^- annihilation cross-section near the Z including initial state radiation*, *Phys. Rev.* **D36** (1987) 2666, doi:[10.1103/PhysRevD.36.2666](https://doi.org/10.1103/PhysRevD.36.2666).
- [155] **L3 Collaboration**, B. Adeva *et al.*, *Measurement of Z^0 decays to hadrons and a precise determination of the number of neutrino species*, *Phys. Lett.* **B237** (1990) 136, doi:[10.1016/0370-2693\(90\)90476-M](https://doi.org/10.1016/0370-2693(90)90476-M).
- [156] W. Hollik, *Radiative Corrections in the Standard Model and their Role for Precision Tests of the Electroweak Theory*, *Fortsch. Phys.* **38** (1990) 165–260, doi:[10.1002/prop.2190380302](https://doi.org/10.1002/prop.2190380302).
- [157] G. Alexander *et al.*, *Electroweak parameters of the Z^0 resonance and the Standard Model: the LEP Collaborations*, *Phys. Lett.* **B276** (1992) 247–253, doi:[10.1016/0370-2693\(92\)90572-L](https://doi.org/10.1016/0370-2693(92)90572-L).
- [158] **Working Group on LEP Energy, ALEPH, DELPHI, L3, OPAL Collaboration**, L. Arnaudon *et al.*, *Measurement of the mass of the Z boson and the energy calibration of LEP*, *Phys. Lett.* **B307** (1993) 187–193, scan: [CERN](https://cds.cern.ch/record/200000).
- [159] **ALEPH, DELPHI, L3, OPAL and the LEP Electroweak Working Group Collaboration**, D. Schaile *et al.*, “Updated parameters of the Z^0 resonance from combined preliminary data of the LEP experiments.” Contributed to Europhysics Conf. on High Energy Physics, Marseille, France, Jul 22–28, 1993 and the Int. Symp. on Lepton Photon Interactions at High Energies, Cornell, Ithaca, NY, Aug 10–15, 1993, [CERN/PPE/93-157.pdf](https://cds.cern.ch/record/200000) and scan: [KEK](https://cds.cern.ch/record/200000).
- [160] **LEP, ALEPH, DELPHI, L3, OPAL, Line Shape Sub-Group of the LEP Electroweak Working Group Collaboration**, *Combination procedure for the precise determination of Z boson parameters from results of the LEP experiments*, [hep-ex/0101027](https://cds.cern.ch/record/200000).
- [161] J. van der Bij, *Two loop large Higgs mass correction to vector boson masses*, *Nucl. Phys.* **B248** (1984) 141, doi:[10.1016/0550-3213\(84\)90591-1](https://doi.org/10.1016/0550-3213(84)90591-1).
- [162] B. Kniehl, M. Krawczyk, J. Kühn, and R. Stuart, *Hadronic contributions to $O(\alpha^2)$ radiative corrections in e^+e^- annihilation*, *Phys. Lett.* **B209** (1988) 337, doi:[10.1016/0370-2693\(88\)90958-6](https://doi.org/10.1016/0370-2693(88)90958-6).
- [163] R. Barbieri, M. Beccaria, P. Ciafaloni, G. Curci, and A. Vicere, *Two loop heavy top effects in the Standard Model*, *Nucl. Phys.* **B409** (1993) 105–127, doi:[10.1016/0550-3213\(93\)90448-X](https://doi.org/10.1016/0550-3213(93)90448-X).
- [164] G. Degrandi, S. Fanchiotti, and P. Gambino, *Current algebra approach to heavy top effects in $\delta(\rho)$* , *Int. J. Mod. Phys.* **A10** (1995) 1377–1392, doi:[10.1142/S0217751X95000668](https://doi.org/10.1142/S0217751X95000668), [[hep-ph/9403250](https://cds.cern.ch/record/200000)].
- [165] L. Avdeev, J. Fleischer, S. Mikhailov, and O. Tarasov, *$O(\alpha_s^2)$ correction to the electroweak ρ parameter*, *Phys. Lett.* **B336** (1994) 560–566, doi:[10.1016/0370-2693\(94\)90573-8](https://doi.org/10.1016/0370-2693(94)90573-8), Erratum–ibid. **B349** (1995) 597–598, [[hep-ph/9406363v2](https://cds.cern.ch/record/200000)].

- [166] K. Chetyrkin, J. H. Kühn, and M. Steinhauser, *Corrections of order $O(g_f m_t^2 \alpha_s^2)$ to the ρ parameter*, *Phys. Lett.* **B351** (1995) 331–338, doi:10.1016/0370-2693(95)00380-4, [hep-ph/9502291].
- [167] S. Eidelman and F. Jegerlehner, *Hadronic contributions to $g - 2$ of the leptons and to the effective fine structure constant $\alpha(M_Z^2)$* , *Z. Phys.* **C67** (1995) 585–602, doi:10.1007/BF01553984, [hep-ph/9502298].
- [168] Y. Schröder and M. Steinhauser, *Four-loop singlet contribution to the rho parameter*, *Phys. Lett.* **B622** (2005) 124–130, doi:10.1016/j.physletb.2005.06.085, [hep-ph/0504055].
- [169] A. Freitas, S. Heinemeyer, W. Hollik, W. Walter, and G. Weiglein, *Calculation of fermionic two loop contributions to muon decay*, *Nucl. Phys. Proc. Suppl.* **89** (2000) 82–87, [hep-ph/0007129].
- [170] A. Freitas, W. Hollik, W. Walter, and G. Weiglein, *Complete fermionic two loop results for the $M(W) - M(Z)$ interdependence*, *Phys. Lett.* **B495** (2000) 338–346, , Erratum–ibid. **B570** (2003) 260–264, hep-ph/0007091v3.
- [171] M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, *Precise prediction for the W boson mass in the standard model*, *Phys. Rev.* **D69** (2004) 053006, [hep-ph/0311148].
- [172] M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, *Towards better constraints on the Higgs boson mass: Two-loop fermionic corrections to $\sin^2 \theta_{\text{eff}}^{\text{lept}}$* , hep-ph/0409142.
- [173] M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, *Two-loop fermionic electroweak corrections to the effective leptonic weak mixing angle in the standard model*, *Nucl. Phys. Proc. Suppl.* **135** (2004) 119–123, [hep-ph/0408207].
- [174] M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, *Complete two-loop electroweak fermionic corrections to $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ and indirect determination of the Higgs boson mass*, *Phys. Rev. Lett.* **93** (2004) 201805, [hep-ph/0407317].
- [175] M. Awramik, M. Czakon, and A. Freitas, *Bosonic corrections to the effective weak mixing angle at $O(\alpha^2)$* , *Phys. Lett.* **B642** (2006) 563–566, [hep-ph/0605339].
- [176] M. Awramik, M. Czakon, A. Freitas, and B. Kniehl, *Two-loop electroweak fermionic corrections to $\sin^2 \theta_{\text{eff}}^{\text{bb}}$* , *Nucl. Phys.* **B813** (2009) 174–187, [0811.1364].
- [177] P. Baikov, K. Chetyrkin, J. Kühn, and J. Rittinger, *Complete $O(\alpha_s^4)$ QCD corrections to hadronic Z decays*, *Phys. Rev. Lett.* **108** (2012) 222003, [1201.5804v3].
- [178] J. Fleischer, J. Fujimoto, T. Ishikawa, A. Leike, T. Riemann, Y. Shimizu, and A. Werthenbach, *One loop corrections to the process $e^+ e^- \rightarrow t \bar{t}$ including hard bremsstrahlung*, hep-ph/0203220.
- [179] T. Hahn, W. Hollik, A. Lorca, T. Riemann, and A. Werthenbach, *$O(\alpha)$ electroweak corrections to the processes $e^+ e^- \rightarrow \tau^+ \tau^-$, $c \text{ anti-}c$, $b \text{ anti-}b$, $t \text{ anti-}t$: A comparison*, hep-ph/0307132. LC-TH-2003-083.
- [180] H. Baer et al., *INTERNATIONAL LINEAR COLLIDER, Technical Design Report - Volume 1, 'Physics at the International Linear Collider'*, ILCPHysicsVolume.pdf.
- [181] D. Bardin, L. Kalinovskaya, S. Riemann, T. Riemann, in preparation.
- [182] LEPEWWG, *LEP/TEV EW WG Plots for Winter 2012*, <http://lepewwg.web.cern.ch/LEPEWWG/plots/winter2012/>.
- [183] H. Flacher, M. Goebel, J. Haller, A. Hocker, K. Monig, and J. Stelzer, *Revisiting the Global Electroweak Fit of the Standard Model and Beyond with Gfitter*, *Eur. Phys. J.* **C60** (2009) 543–583, doi:10.1140/epjc/s10052-009-0966-6, [0811.0009v3].

- [184] H. Flücher, M. Goebel, J. Haller, A. Hoecker, K. Mönig, and J. Stelzer, *Erratum to: Revisiting the global electroweak fit of the Standard Model and beyond with Gfitter*, *Eur. Phys. J.* **C71** (2011) 1718, doi:[10.1140/epjc/s10052-011-1718-y](https://doi.org/10.1140/epjc/s10052-011-1718-y).
- [185] P. Baikov, K. Chetyrkin, and J. Kühn, *Order $\alpha^4(s)$ QCD corrections to Z and τ decays*, *Phys. Rev. Lett.* **101** (2008) 012002, [[0801.1821](https://arxiv.org/abs/0801.1821)].
- [186] G.-C. Cho and K. Hagiwara, *Supersymmetry versus precision experiments revisited*, *Nucl. Phys.* **B574** (2000) 623–674, [[hep-ph/9912260](https://arxiv.org/abs/hep-ph/9912260)].
- [187] K. Hagiwara, S. Matsumoto, D. Haidt, and C. Kim, *A Novel approach to confront electroweak data and theory*, *Z. Phys.* **C64** (1994) 559–620, E: **C68** (1995), [[hep-ph/9409380v1](https://arxiv.org/abs/hep-ph/9409380v1)].
- [188] G.-C. Cho, K. Hagiwara, Y. Matsumoto, and D. Nomura, *The MSSM confronts the precision electroweak data and the muon g-2*, *JHEP* **1111** (2011) 068, [[1104.1769](https://arxiv.org/abs/1104.1769)].
- [189] S. Riemann, *Precision electroweak physics at high energies*, *Rept. Prog. Phys.* **73** (2010) 126201, doi:[10.1088/0034-4885/73/12/126201](https://doi.org/10.1088/0034-4885/73/12/126201).
- [190] J. Blümlein and Riemann, T., (eds.), *Loops and legs in quantum field theory. Proceedings, 5th Zeuthen Workshop on elementary particle theory, Bastei, Germany, April 9-14, 2000*, *Nucl. Phys. Proc.Suppl.* **89** (2000) 322P.